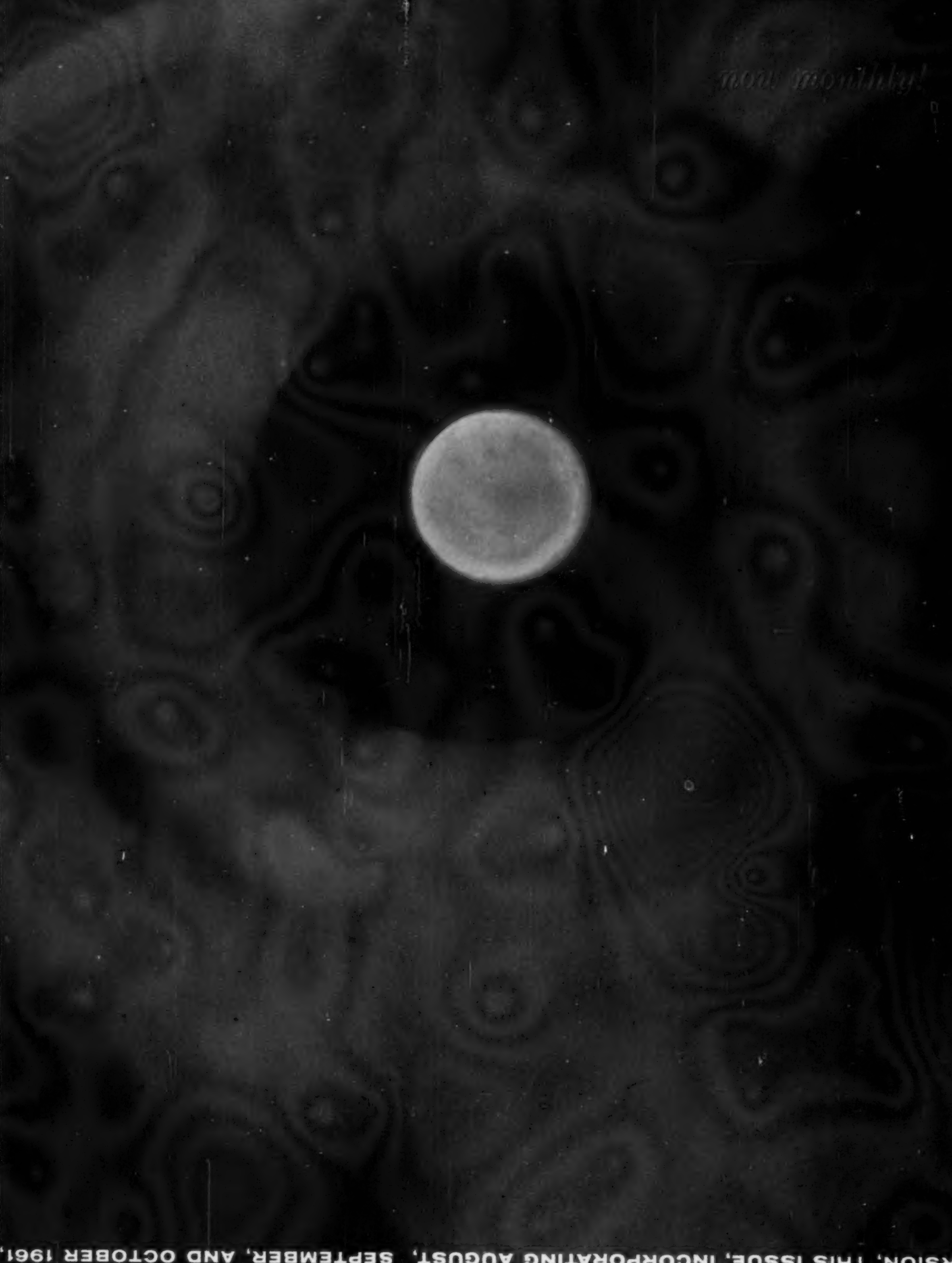
INDUSTRIAL RESEARCH

OCTOBER 1961

A SPECIAL EDITION (TWO DOLLARS) DEVOTED ENTIRELY TO THE PROFITABLE NEW SCIENCE OF ENERGY CONVERSION, THIS ISSUE, INCORPORATING AUGUST, SEPTEMBER, AND OCTOBER 1961, MARKS THE FIRST MONTHLY PUBLICATION OF INDUSTRIAL RESEARCH, THE ONLY TECHNICAL MAGAZINE WRITTEN EXPRESSLY FOR MANAGEMENT IN GOVERNMENT AND INDUSTRY.

now monthly!



OCTOBER 1961 **RE**

THE COVER *photograph—showing the cathode area of an energy converter—emulates the sun, basic source of all earth's energy, as if it were shining through a hurricane. Believed to be the first color photo every made of the cathode area of an all metal-ceramic vapor-type thermionic energy converter, the photo was taken at the RCA Electron Tube Div. Laboratories in Lancaster, Pa. The red tones of the cover are reflections from the face of a pyrometric viewing tube used to look into the cathode area. The redness is caused by two infrared lamps required to heat the inner surface of the viewing window to over 390 F to prevent deposition of cesium vapor, which would have interfered with the photograph. Pyrometric cathode temperature at the time of the photo was 2140 F.*

The thermionic energy converter in the photograph typifies the subject of this entire special edition: the direct conversion of energy to electricity. Energy conversion experts Dr. J. A. Welsh, the late Dr. Joseph Kaye (who died only four days after completing the article), and nuclear authority Dr. C. E. Crompton are among the distinguished authors contributing articles for this truly definitive annual reference edition.

As the annual reference issue, this edition also marks the first of monthly publication of Industrial Research, the only technical magazine for management. I·R was begun in January, 1959 as a quarterly; it was published bimonthly during 1960 and part of this year; and is now monthly.

This issue is unique in several other ways. It is the first published from our new office building and typesetting plant in Beverly Shores, Ind. It is the first to be printed 54,000 times. And it is the first published with the cooperation of American Research & Development Corp., Boston, a substantial new investor in Industrial Research magazine. American Research, the largest and first publicly-owned venture capital investment company, specializes in financing fast-growing scientifically oriented companies, such as The Barden Corp., Camco Inc., Airborne Instruments Laboratory Div. of Cutler-Hammer, Itek Corp., Ionics Inc., Tracerlab Inc., The Geotechnical Corp., Digital Equipment Corp., Teradyne Inc., Adage Inc., and many others.

ENERGY CON-VERSION

A new feature, "The I·R Dictionary for Technical Management," is introduced in this issue on page 8. Designed as a reading aid, the dictionary will present concise definitions of technical terms appearing in Industrial Research articles each month. ■

54,000 copies of this issue printed.
Circulation audited and verified.

Industrial Research is dedicated to reducing the time lag between invention and production. It seeks to do this by informing technical management of new scientific developments and their profitable applications in all fields of industry.

INDUSTRIAL RESEARCH
BEVERLY SHORES, INDIANA

Subscriptions: \$7 for one year (12 issues); \$12 for two years; \$15 for three years, to United States; \$2 extra for each 12 issues to foreign countries and Canada. Foreign remittance by International Money Order payable at Chicago, Ill., U.S.A. When changing address, please notify Circulation Dept. at address above. Notification of changes of job title are requested.

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Editorial: Professional science writers, industrial executives, research workers, educators, artists, and photographers are invited to query the editor at address above, with ideas for articles or art. Do not send manuscripts without query. Answers to queries are prompt.

INDUSTRIAL RESEARCH

OCTOBER 1961

THE TECHNICAL MAGAZINE FOR MANAGEMENT

(see page 88)

Dr. Lee de Forest, distinguished member of the Industrial Research Editorial Board, passed away June 30, 1961 in Hollywood, Calif. Dr. de Forest was the inventor of the first electronic tube and radio telephone.

the 14th issue of I·R

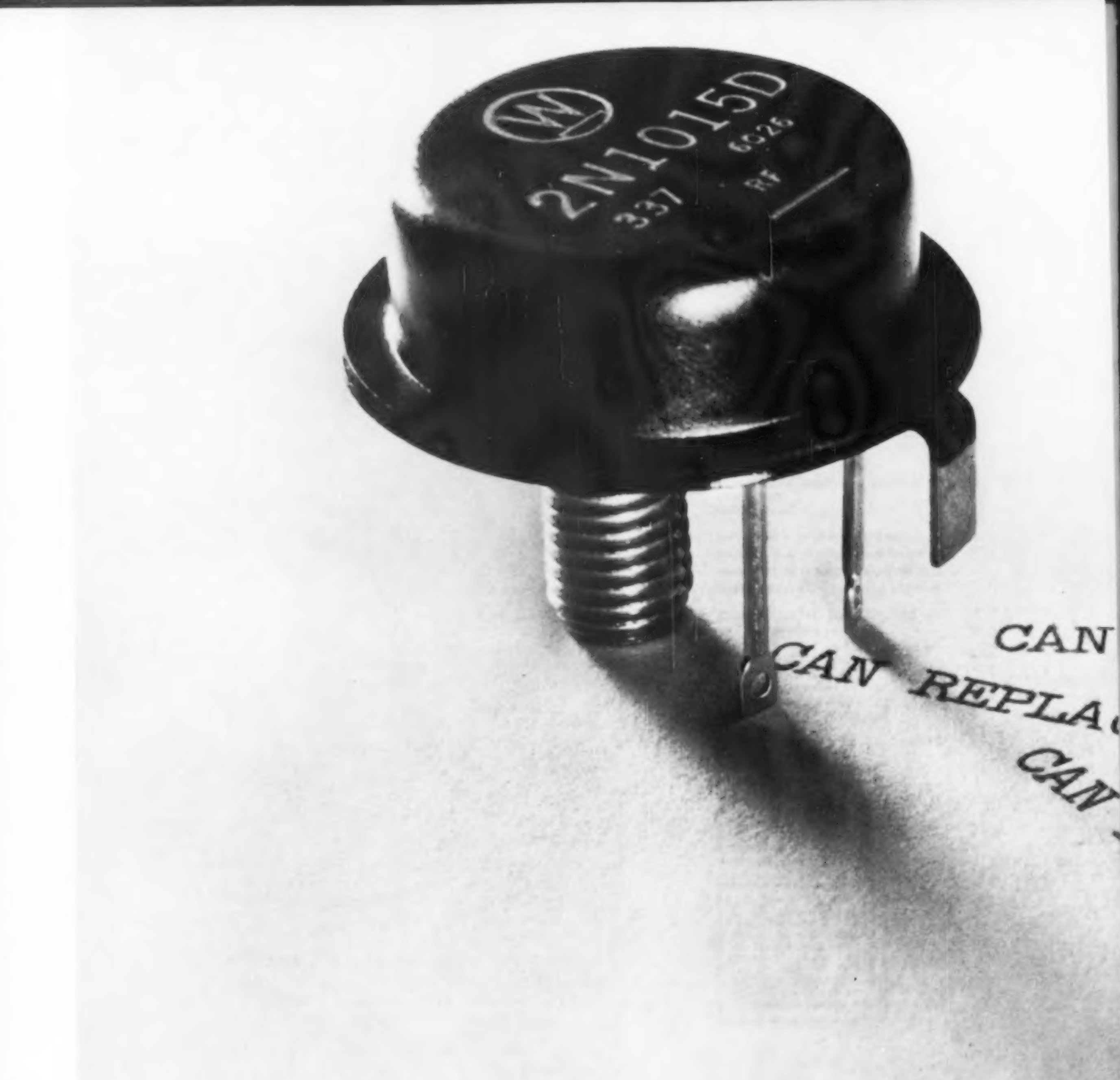
14

***INDUSTRIAL RESEARCH:** editorial, circulation, and advertising offices, Beverly Shores, Ind. Vol. 3, No. 4, October, 1961, published monthly by Industrial Research Inc.*

Copies of I·R on microfilm are available from University Microfilms, 313 N. First St., Ann Arbor, Mich. (See page 4 for subscription and other information.)

ARTICLES

DEPARTMENTS



greater derating margin for higher reliability...at lower cost than lower rated types

Westinghouse 2N1015 and 2N1016 transistors—Circuits which use power transistors can be upgraded in reliability by changing to the Westinghouse 2N1015-2N1016 series. The low saturation resistance and high dissipation rating (150 watts) of these transistors mean cooler operation—more safety factor in service. In fact, the 2N1015-2N1016 series offers twice the derating margin you can get in competitive types. Their high voltage ratings—up to 200 volts V_{CE}—also mean an end to series connections of lower rated types. Yet all this is yours at less cost than you are now paying.

In addition to these many circuit advantages, the 2N1015-2N1016 transistors give you the reliability assurance of


REPLACE 2N1489
CAN REPLACE 2N389
E 2N1490
CAN REPLACE 2N1070
EPLACE 2N1069

THE I·R DICTIONARY

for technical management

EDITOR'S NOTE: *The I·R Dictionary for Technical Management is introduced in this issue to provide readers with a broader understanding of the technical terminology that appears in Industrial Research articles. While some of the terms defined may seem elementary to some technical management men, others have expressed a need for such a dictionary to help them understand new and old terms outside their fields of specialization. The I·R Dictionary each issue will be concerned only with technical terms used in the articles of that issue. The following definitions all are necessary for a complete understanding of energy conversion, the subject of this special edition.*

absorption efficiency—the ratio of thermal energy retained by a solar absorber to the radiant energy directed to the absorber.

array—an ordered grouping of components.

Carnot theorem—a thermodynamic principle stating that a cycle continuously operating between a high temperature and a low temperature cannot be more efficient than a reversible cycle operating between the same two temperatures. In 1821, Nicholas Carnot established the factors which affect the efficiency of engine cycles and stated the conditions for maximum efficiency to make the Carnot theorem one of the most important contributions to thermodynamics.

electrostatic generator—a high-voltage generator in which the voltage is produced by mechanically transporting electrical charges from plates of lower to higher potential. The most common form, invented in 1929 by Dr. R. J. Van de Graaff, uses a non-conducting belt to carry charges to a terminal, which thereby develops a high potential. Because of this high potential, there exists along the belt an electrical gradient against which the charges have to be carried.

enthalpy—the sum of thermal internal energy plus flow work (displacement energy), or the heat effect in a constant pressure process when only compression or expansion occurs. The change in enthalpy is the change in the internal energy, plus the work of compression or expansion.

entropy—a measure of the unavailable or locked-up energy in a thermodynamic system. The entropy change of the system times the absolute temperature at the heat sink reveals the unavailable energy.

free energy—the amount of available energy from a thermodynamic system.

fuel cell—an electrochemical device in which reactants are fed continuously from an external source for the direct production of electricity from chemical energy. A basic unit consists of an electrolyte and two electrodes; the fuel is oxidized at one, and the oxidant is reduced at the other. The maximum energy recovered is equal to the free energy of the reaction.

heat pump—a refrigeration-type machine used for heating rather than cooling. By means of a compressible refrigerant, heat is transferred from a low-temperature body, such as the atmosphere, the earth, or a lake, to the environment that is to be heated. The heat transfer can be greater than the thermal equivalent of the mechanical energy expended by the pump (the inverse of the Carnot principle).

heat sink—an absorber of heat. A heat sink normally stays at a low temperature because it dissipates heat away by radiation or conduction.

ionization potential—the work necessary to remove an electron from the outermost or valence shell of an atom.

magnetohydrodynamics (MHD)—the science of the interaction between magnetic fields and electrically conducting fluids or gases.

MHD generator—similar in principle to a conventional generator in that an electrical conductor moving through a magnetic field generates a voltage. However, the MHD generator puts a stream of high-temperature, ionized gas through a magnetic field, where the conventional generator uses a solid conductor driven by a turbine. Thus a solid moving part is replaced by the plasma and the turbine is eliminated.

Peltier effect — French watchmaker Jean Peltier discovered in 1834 that when a current flowed across the junction of two dissimilar materials, the junction was heated or cooled by an amount proportional to the current, depending upon the direction of the current. From this principle, small compact heat pumps utilizing a number of Peltier "junctions" now are being made.

photoelectric effect—the interaction between radiation and matter resulting in the absorption of photons and consequent production of mobile charge carriers.

photovoltaic converter—a device that utilizes the photovoltaic effect in converting light to electric energy.

photovoltaic effect—the production of an electromotive force by incidence of radiant energy, commonly light, upon the junction of two dissimilar materials.

plasma—a neutral body of ionized gas.

Seebeck effect—German physicist Thomas Seebeck discovered in 1822 that a current is produced in an electrical circuit composed of the junction of two dissimilar metals when one junction is held at a higher temperature than the other. The phenomenon resulting in this potential difference is known as the Seebeck effect.

sinusoid—a curve whose ordinates are proportional to the sine of the abscissa. In a Cartesian graph, the ordinate usually is the vertical coordinate and the abscissa is the horizontal coordinate.

solar absorber—a surface which converts solar radiation into thermal energy.

solar cell—a photovoltaic converter which usually is used for converting solar to electrical energy.

solar concentrator—a device for increasing the intensity of solar energy by optical means.

solar energy conversion—a changing of solar radiation, either directly or with a heat engine, to electrical or mechanical power.

space charge—a buildup of electrons near an emitter. The equilibrium current flow is reached when the electric field produced by the electron cloud in "space" near the emitter is sufficiently strong to prevent any subsequent emission.

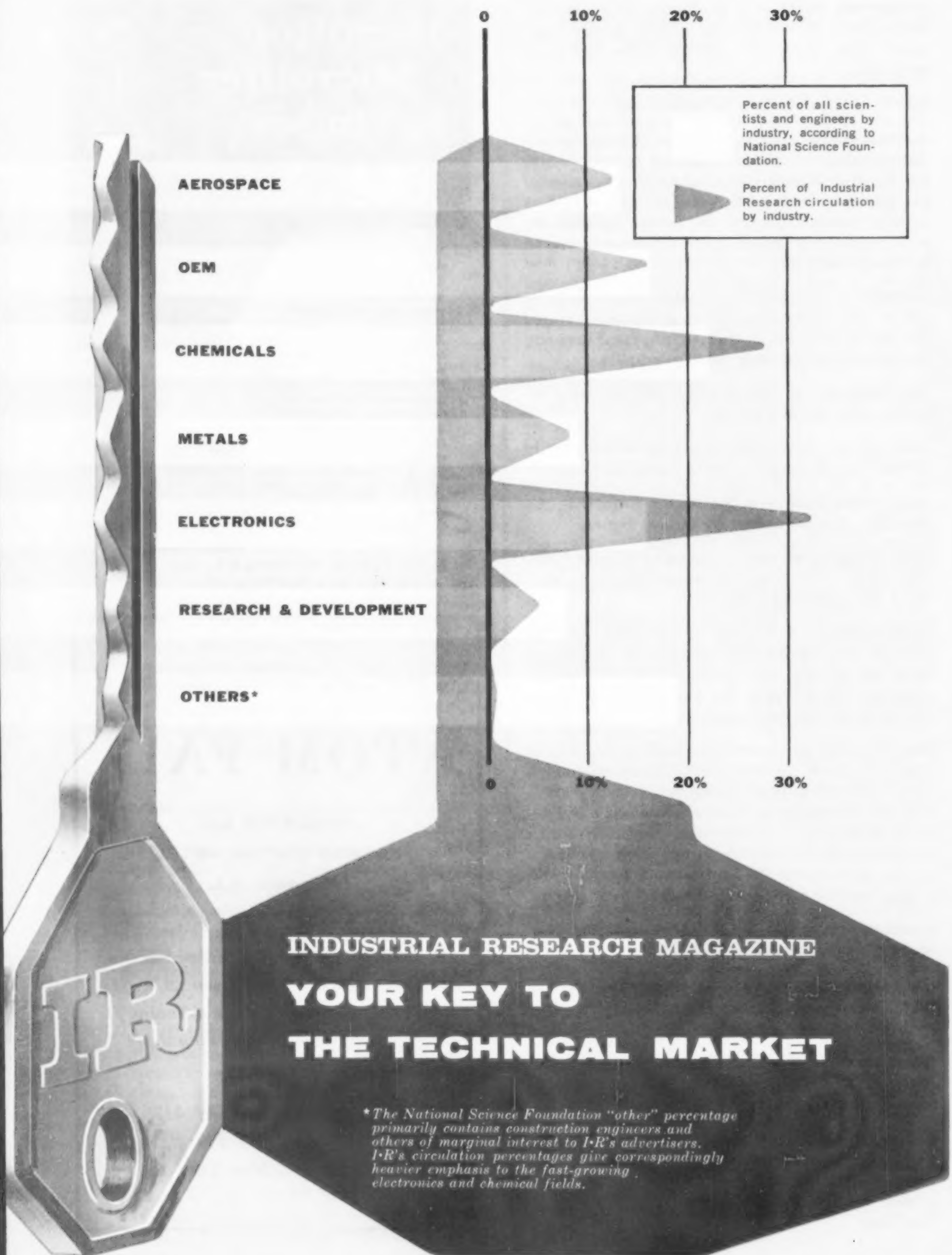
thermionic energy conversion—direct production of electricity from the emission of electrons from a heated substance. The working fluid in both thermionic and thermoelectric converters consists of electrons. However, in a thermionic converter, a high temperature is required to give the electrons enough energy to overcome the emitter work function and escape into the inter-electrode space.

thermionic converter—a device that utilizes thermionic emission in changing thermal to electric energy.

thermoelectric converter—a device that utilizes thermoelectric effect in changing thermal to electric energy.

thermoelectric effect—an electromotive force results from a difference of temperature between two junctions of dissimilar materials in the same circuit.

thermocouple—two conductors of different metals are joined together to produce a loop in which a thermoelectric current flows when there is a difference in temperature between the two sets of junctions.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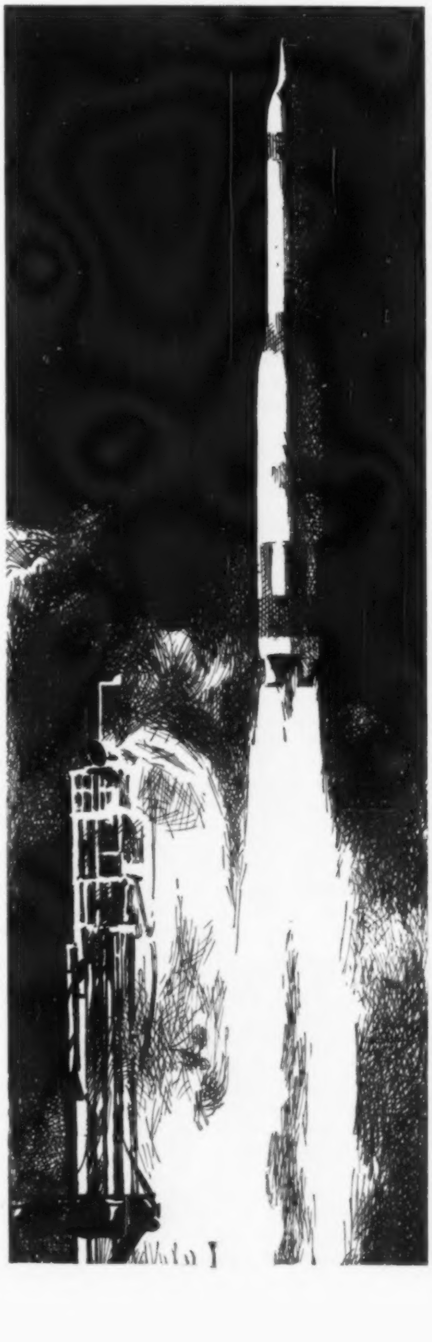
*The National Science Foundation "other" percentage primarily contains construction engineers and others of marginal interest to I·R's advertisers. I·R's circulation percentages give correspondingly heavier emphasis to the fast-growing electronics and chemical fields.

Prizes wrested from the Fluorine "Dragon"

". . . but the prize was guarded by a dragon fiercer than the sleepless, fire-breathing monster Jason faced to win the Golden Fleece."

The quotation is from our new brochure, *Fluorine*. Chemists will understand the metaphor. They're quite accustomed to hearing fluorine called hard names. It's the most reactive element in the periodic table—often termed "the chemical outlaw."

The brochure traces the development of fluorine from its isolation in 1886 to the present. It points out "prizes" wrested from the volatile dragon: the latest advances in aerosols, nuclear power, insulation, medicine, rocketry. And it includes contributions from our General Chemical Division, pioneer in fluorine chemistry for over 60 years and now America's largest supplier of fluorine chemicals, with a list of more than 100 such products.



"Dragon" in a vacuum bottle. Until recently, extensive use of fluorine was handicapped by handling and shipping problems. Only small amounts could be transported—and in gaseous form at that. Several years ago, our General Chemical research people learned how to ship fluorine as a *liquid* in *bulk*. They devised a triple-tank truck, much like a giant vacuum bottle, with liquid fluorine in the innermost tank. Next, liquid nitrogen to cool fluorine below its boiling point of –306°F. Finally, a vacuum-insulated jacket. Now 5,000 pounds can be shipped by truck. And the door was opened to large-scale use.

Fluorine and atomic energy. In the nuclear energy field, a development by our research people permits the company to make exceptionally high-purity uranium hexafluoride, basic atomic raw material, by a unique and simpler process than that used by government-owned plants. Our plant, located at Metropolis, Ill., is the first privately owned facility to produce this basic atomic raw material for the Atomic Energy Commission. Last year, Allied delivered its 10-millionth pound of UF_6 to the A.E.C.

Rocket engines get a new "boost." Chances are, the first man on the moon may get there "via fluorine." The enormous energy liberated by the reaction of liquid fluorine and liquid hydrogen yields higher specific impulse (the key to rocket performance) than any stable chemical combination yet known. The first full-scale firings of a complete turbo-pump-fed rocket engine using these elements as propellants have already taken place.

New packaging film makes debut. It's ACLAR®, our new fluorohalocarbon film . . . characterized by fantastically low moisture vapor transmission, transparency, impact strength. To get the moisture barrier benefits of ACLAR type 33 film, a saran film would have to be over 100 times as thick, a polyethylene film over 400 times as thick, and a polyester film over 700 times as thick. Indicated uses: packaging electronic and other delicate mechanical equipment components, drugs, and chemicals. Its application in *your* field of interest might be of value to *your* product, too. Why not explore the possibilities of ACLAR?

Write today for our new brochure, *Fluorine*. Your name and title on your company letterhead will bring you a copy promptly. The address: Allied Chemical Corp., Dept. 61-IR, 61 Broadway, New York 6, New York. Or phone HAnover 2-7300.

Allied Chemical

Basic to America's Progress

IR FEEDBACK *from technical management*

English channel tunnel

Sir:

I was much impressed by your article, "The English Channel Tunnel: 159 Years of Research," in Vol. 3, No. 3 (June-July); in fact, it completely disrupted my morning's work. However, I do find a minuscule error on page 48, where you say a propeller-driven train would have a "second source of ventilation." Tain't so. A wheel-driven train only moves by forcing air backward. Thus a propeller-driven train would push *less* air through a tunnel than a wheel-driven train.

A Buffalo Forge engineer told me the estimate on how much air cars would pull through the Holland tunnel was conservative. Turns out, you don't need the ventilation fans at all.

If the propeller tip clearance is small (1 or 2% of blade width), efficiency can be very high (95 to 97%). And for your amusement, the air downstream of a propeller in a wind tunnel is moving *slower* than upstream. It is at a higher static pressure and hence needs less velocity to pass a given mass per second. Don't tell anybody; you'll only start an argument.

Alan Pope
Head, Aero & Thermodynamics
Sandia Corp.

Sir:

I first became familiar with the English Channel Tunnel idea while working at DeLeuw, Cather & Co., Chicago, and did a paper on the subject in connection with my present studies at Cornell University School of Engineering, so I was very much pleased to read your article.

I especially enjoyed the article because it deals mainly with engineering aspects of the proposed tunnel project. While doing research on my paper, I was able to find large amounts of material on political and economic angles, but little on technical requirements.

Thank you for a most informative article, and in fact, a very interesting magazine.

Clifford Argue
Cornell University

Molectronics

Sir:

"The Molectronics Engineer — A New Species," while non-technical in presentation, was well done and nicely presented. It seems to me that this is a good example of the type of article which Industrial Research should be presenting to management.

The concept of the "molectronics engineer" who is competent in all phases of technology is interesting but does not follow the historic example of the semiconductor industry where many scientists, each skilled in a particular discipline, work effectively as a team to produce a new concept. The wide breadth of technologies necessary in the solid state field seems to me to argue against the usefulness of the "scientific generalist" in solving specific problems.

It is implied that Texas Instruments' solid circuit semiconductor networks were developed under an Air Force contract. Actually, the concepts used in this area were generated and proved out in company-sponsored research.

R. W. Olson
Vice-President
Texas Intruments Inc.

Sir:

Harrell Nobel's article on molectronics certainly conveyed the excitement of the tremendous potential of work in this area. As such it provides ample stimulation to promote this general field.

Malcolm R. Currie
Manager, Physics Laboratory
Hughes Research Labs.

Sir:

"The Molectronics Engineer — A New Species" (Vol. 3, No. 3) was extremely helpful in making our people aware of the trends in the molecular electronics field. It also was very timely in that it preceded Westinghouse's release in Business Week as well as the more comprehensive survey in Electrical Engineering which appeared several days later.

The material was well written, interesting, and quickly brought me up to date on the state-of-the-art. Keep up the good work.

Morris Brenner
Vice-President, Engineering
Penn-Union Electric Corp.

Transposed chief

Sir:

I have been called many names over the past 64 years, but the one on the attached mailing label (Thief Engineer) is to say the least new and novel.

Although I was Chief Engineer of a now defunct company for many years, I can assure you that the demise of that company as a quality manufacturer was not due to larceny in the engineering department. By and large, engineers do not seem to be too well qualified to seek out legal loopholes and indulge in stock raiding and manipulation to obtain the quick buck.

Incidentally, Industrial Research appears to be an excellent magazine and should find wide acceptance.

D. L. Boyd
Professional Engineer
Boyd Associates

Aircars

Sir:

I am personally interested in Dr. R. B. Sleight's article, "Aircars and the 'Terresphere'" (Vol. 3, No. 3). Members of our company are interested in all phases of industrial research, particularly where it touches on our own interest in mining and milling of molybdenum concentrates. I hope you may have some material on a new process for drilling that employs ultrasonics.

C. J. van Oosten
Montana Molybdenum Corp.

Product development

Sir:

I was extremely interested in Dr. Charles Moore's article, "Basic Approach to Product Development" (Vol. 3, No. 2).

John A. Coe
Vice-President
The Anaconda Co.

Automated teaching

Sir:

We are preparing for publication to business colleges a textbook entitled "Automation for Business Students." The last half of the book will be made up of articles from magazines telling about applications and interesting features incorporating automation into everyday living.

In one chapter, we tell people how to prepare for careers in an automated business world. In this chapter we would like to reproduce and use the article "Education Machines — A Trend Toward Automated Teaching" (Vol. 3, No. 1). This article, by Dr. R. E. Packer, is an excellent discussion of many things in which our schools are interested.

John Burger
Managing Director
Automation Institute Courses

Copying machines

Sir:

The article, "Speedup in Office Copying" (Vol. 2, No. 6), specified that "only two U.S. companies, Apeco and Anken, manufacture copy paper for use in diffusion copiers."

This statement is not correct. We have been coaters of photographic materials since 1939 and have coated diffusion-transfer photo-copy paper for marketing throughout the country since approximately 1951. These diffusion-transfer office copy materials are coated for sale under the Peerless label as well as other private labels belonging to firms of significance in the field.

Our line is a complete one, consisting of three different speed negative papers and four types of positive papers. These materials are designed for use on transfer process photocopy machines we have manufactured, as well as on most competitive machines.

Walter H. Jacobs
Sales Promotion Manager
Peerless Photo Products Inc.

Flameless heat

Sir:

Your article, "Heat Without Flame" (Vol. 2, No. 2), has become part of our information files in the Long Range Planning Industrial Information Center. In an effort to keep these files up to date, further information on thermocatalytic combustion would be appreciated.

Mrs. Viona R. Duncan
Research Analyst
Stanford Research Institute

Happy author

Sir:

I have heard from several people who have read my article "Realistic Research Administration" (Vol. 3, No. 3), and had some comments about it (even from Technicolor Corp., which objected mildly because the word "Technicolor" was not capitalized in the article). I was pleasantly surprised at the favorable response.

I have enjoyed working with your staff and was pleased with the way you were able to spark up the article visually.

H. W. Rice
Director of Research
Robertshaw-Fulton Controls Co.
Western Research Center

Feedback on feedback

Sir:

This is in reply to Harry B. Fuchs' letter (Vol. 3, No. 3) in which he discusses Prof. John A. Wheeler's theory of lines of force in curved space-time.

In support of this theory, Fuchs cites from his copyrighted essay, "God's Circle," several excerpts wherein it is assumed that the cosmic creative process is based on the circle or segments thereof.

While I do not wish to argue the merits of the circular concept, I would like to point out that in Wheeler's theory, the lines of force certainly are not confined to circles or circular segments. In limited space-time, the circle simply will not coincide with the limits. A true circle in space most certainly would be a physical freak, as would the true sphere. We must not allow our thinking to be confused and confined by true analytical figures.

In a truly limitless yet finite space, a straight line from a point in this space must surely return to cross this point again.

John Clifton Oubre
Petroleum Chemicals Inc.

RESEARCH TRENDLETTER
is going
WEEKLY *see page 40*

Advisory board

Sir:

I've had a number of congratulatory calls on my Industrial Research Advisory Board appointment. By the general comments I've had, and by the level of persons from whom I've heard, there seems to be an acceptance of Industrial Research that you should consider an extremely encouraging portent for the future.

If I were to attempt to characterize the special editorial function I•R is coming to be known for, I'd say it is the presentation of well-written reviews for the technical sophisticate of those contemporary developments that have particular potential for high technology. To my personal knowledge, there's no other publication that quite fits this very important role.

DeWitt O. Myatt
President
Science Communication Inc.

General feedback

Sir:

I have been receiving your publication for some time now and find it very informative and interesting. In fact, I circulate my copy to our general manager and product planning manager.

F. J. Lohan
Manager
Research & Development
Bryant Computer Products

Sir:

I look forward to Industrial Research with a great deal of interest.

Donald W. Collier
Vice-President, Research
Borg-Warner Corp.

Sir:

I long have considered that Industrial Research is an excellent source for the latest engineering information. The magazine is available here to a group of five engineers who are engaged in the development around the Discoverer, Midas, Samos, and Advent Satellite programs.

Guenther G. Schoen
Senior Components Engineer
Lockheed Missiles & Space Co.
Lockheed Aircraft Corp.

Sir:

I found the April-May issue of Industrial Research very interesting with a great breadth of coverage. You should be congratulated on the quality of your Editorial Advisory Board.

William W. Seifert
Assistant to the Dean
School of Engineering
Massachusetts Institute of Technology

Sir:

From what I have seen, Industrial Research is certainly well written and the subject material is one that is of interest not only to technical management but others in the management field.

R. B. Young
President
Acushnet Process Co.

Sir:

I look forward to reading Industrial Research with interest, especially since our business is very closely related to the fields you are covering.

William E. Barbour Jr.
Magnion Inc.

Sir:

I am not a technical man and, therefore, probably not well qualified to offer criticism of your publication. However, my impressions are that Industrial Research is an excellently prepared magazine and would appear to be particularly useful for the technical people in management. It seems to consolidate a great deal of information that one might have to look into a number of magazines to obtain quite as fully.

Needless to say, I wish you the best of success with the publication.

Tilden Cummings
President
Continental Illinois National Bank & Trust Co. of Chicago

Congressional feedback

(Editor's note: Because of their need-to-know, members of the U.S. Senate and House of Representatives as well as certain other government officials have been given subscriptions to Industrial Research as a public service. Following are some comments that have been received.)

Sir:

Industrial Research, I am sure, will provide much useful data. Very shortly I plan to reintroduce legislation to establish a Federal Commission on Science and Technology, which would examine the federal government's future role in national defense research, space science, and in facilitating civilian, industrial, university, and other efforts.

Sen. Hubert H. Humphrey
Minnesota

Industrial Research is certainly a most interesting and informative magazine. I am very interested in the new developments in applied science and you may be sure I am glad to have this publication for my reference library.

Rep. Samuel N. Friedel
7th District, Maryland

I have read with great interest the informative discussion of technological developments in Industrial Research. The information is valuable as reference and I shall certainly bring it to bear on pertinent studies.

Sen. Ralph Yarborough
Texas

I find that in this transition in which we are presently involved any information I can get to clarify the atmosphere of the unknown is certainly beneficial in handling defense appropriations in which I have responsibility.

Rep. Harry R. Sheppard
27th District, California

I have examined your unique publication with great interest.

Rep. Charles A. Halleck
2nd District, Indiana

. . . it will provide very helpful information.

Sen. Barry Goldwater
Arizona

Let me assure you that I read Industrial Research with interest.

Sen. Joseph S. Clark
Pennsylvania

I have found Industrial Research of great interest and benefit.

Rep. Marguerite Stitt Church
13th District, Illinois

I am glad to receive Industrial Research.

Sen. Clifford P. Case
New Jersey

I found the June-July issue both informative and interesting.

Rep. James Roosevelt
26th District, California

Industrial Research is certainly a very nice magazine, highly interesting, and warrants what has been said about it.

Rep. J. Floyd Breeding
5th District, Kansas

. . . . it will prove valuable as a source of information.

Sen. John Marshall Butler
Maryland

This information will be extremely helpful as a legislator.

Rep. James F. Battin
2nd District, Montana

I enjoy reading Industrial Research.

Rep. John V. Lindsay
17th District, New York

. . . many interesting articles in Industrial Research.

Sen. Hjalmar C. Nygaard
North Dakota

With the ever growing importance of research to industry, Industrial Research is a valuable and useful addition to my reference material.

Sen. Lee Metcalf
Montana

. . . I greatly appreciate receiving information on industrial and government research and development effort and wish to commend you for your desire to provide such information in easily understood language.

Rep. Jack Westland
2nd District, Washington

It is important that those of us in Congress be kept fairly current on research and development efforts in understandable terms. You may be sure that I will read ensuing issues of your publication with interest and will send you my view on anything that I believe would be of mutual interest.

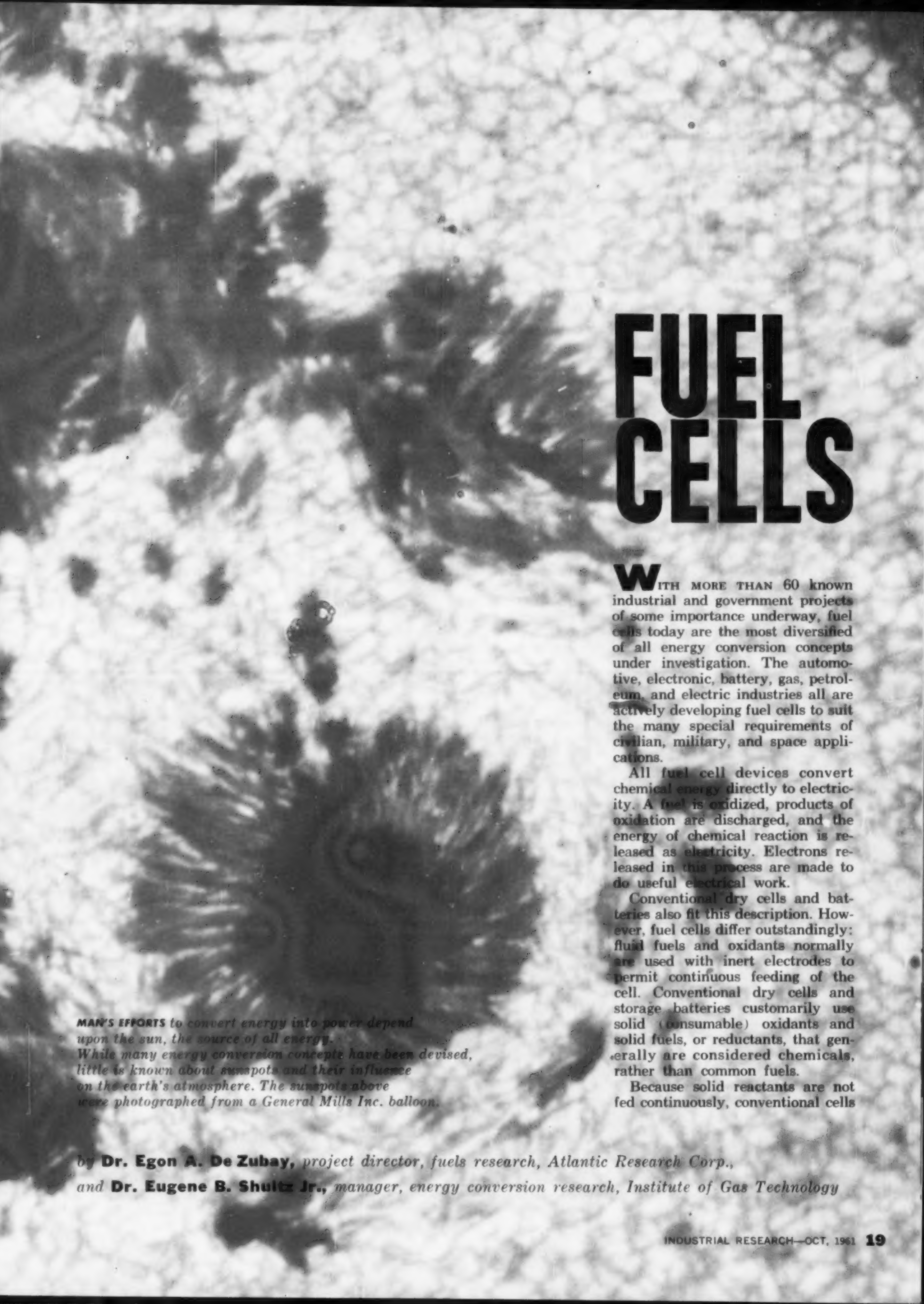
Sen. Henry Dworshak
Idaho

Industrial Research contains much of interest and I look forward to receiving subsequent issues.

Sen. Frank Church
Idaho

Industrial Research is obviously a journal which contains a great deal of essential and useful information.

Lyndon B. Johnson
Vice-President
United States of America



MAN'S EFFORTS *to convert energy into power depend upon the sun, the source of all energy. While many energy conversion concepts have been devised, little is known about sunspots and their influence on the earth's atmosphere. The sunspots above were photographed from a General Mills Inc. balloon.*

FUEL CELLS

With more than 60 known industrial and government projects of some importance underway, fuel cells today are the most diversified of all energy conversion concepts under investigation. The automotive, electronic, battery, gas, petroleum, and electric industries all are actively developing fuel cells to suit the many special requirements of civilian, military, and space applications.

All fuel cell devices convert chemical energy directly to electricity. A fuel is oxidized, products of oxidation are discharged, and the energy of chemical reaction is released as electricity. Electrons released in this process are made to do useful electrical work.

Conventional dry cells and batteries also fit this description. However, fuel cells differ outstandingly: fluid fuels and oxidants normally are used with inert electrodes to permit continuous feeding of the cell. Conventional dry cells and storage batteries customarily use solid (consumable) oxidants and solid fuels, or reductants, that generally are considered chemicals, rather than common fuels.

Because solid reactants are not fed continuously, conventional cells

by **Dr. Egon A. De Zubay,** *project director, fuels research, Atlantic Research Corp.,*
and **Dr. Eugene B. Shultz Jr.,** *manager, energy conversion research, Institute of Gas Technology*

and batteries generate electricity only until the oxidant and reductant are used up. In fuel cells, common fluid fuels, such as hydrogen, carbon monoxide, propane, natural gas, and methyl alcohol, can be used with common oxidants, notably air and oxygen.

There are some exceptions to these rules. Some cells combine a solid, consumable fuel electrode with an air electrode (inert, and continuously fed with air). However, such combinations still are referred to as fuel cells.

High efficiencies at room temperature

Thermodynamically, fuel cells are constant temperature-constant pressure devices, and the maximum energy yield is equal to the change in free energy between products and reactants. For most fuel cells, such as hydrogen and the hydrocarbons, with air or oxygen as oxidant, the free energy change near room temperature is almost as large as the heat of combustion of the fuel. Thus, theoretical efficiencies, expressed as a percentage of the heat of combustion, approach 100%.

In practice, efficiencies substantially higher than 50% are fairly common in laboratory cells; as high as 80% has been reported. High efficiency usually is the most important consideration in choosing fuel cells over other energy conversion devices for a given application. Another important consideration is the possibility of operating at low ambient temperatures.

Fuel cells are not heat engines like thermoelectric and thermionic devices and conventional steam turbogenerators. Therefore, they are not limited by the Carnot efficiency (see page 8 for definition). High temperatures are not necessary to raise the efficiency, but are used in some fuel cells to make ordinarily unreactive fuels more reactive, or to increase the current output.

Construction and operation

All fuel cells must have the three essentials of any electrolytic cell: anode (fuel electrode), cathode (oxidant electrode), and the intervening electrolyte. These components make up a sandwich. Housings must be provided at both electrodes to conduct the fuel and oxidant over the anode and cathode surfaces.

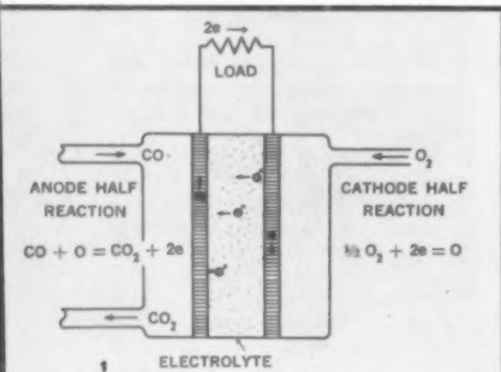
Fuel cell construction methods vary markedly, depending primarily on operating temperatures. Low-temperature cells can use carbon, graphite, or metallic electrodes, and plastic housings. Higher temperature cells require stainless steel bodies and metal or metal oxide electrodes; ceramic matrices are used to hold molten electrolytes.

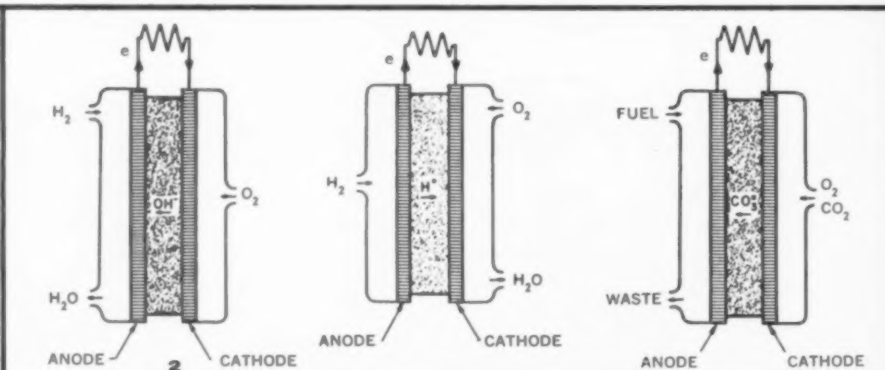
In most fuel cells, fluid fuel and oxidant flow past porous "diffusion" electrodes, and diffuse into the interior of the electrode. At the same time, a liquid electrolyte diffuses into the electrode, and an electrochemical reaction takes place at interfaces and surfaces within and on the electrode.

Obstacles to application

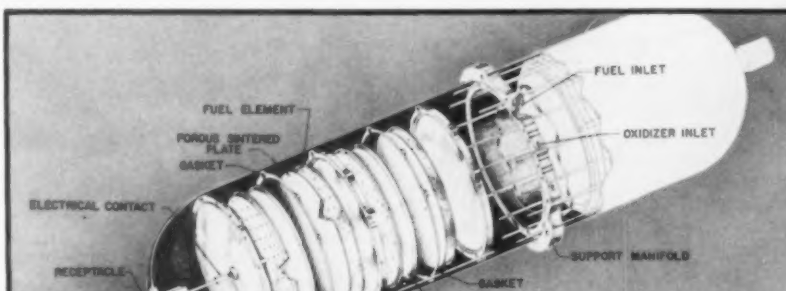
If technical problems in constructing large power packages can be solved, fuel cells would be economically attractive for industrial power. However, complex auxiliary electronic equipment is required. Because the cell is limited to voltages of about 1 to 1.5 volts, a number of cells must be connected in series to produce usable d-c voltages. This requires that individual cells be electrically insulated from one another, but at the same time, fuel and air connections must be made to each cell.

Since a high-temperature molten carbonate cell currently is the best contender for future large-scale industrial use, problems associated with series connections, corrosion, and electrolyte losses become formidable. Even so, according to investigators at Leesona Moos Laboratories, Jamaica, N.Y., the molten carbonate Carbox(R) cell can be built for about \$100 to \$250 per kilowatt





FUEL CELL *construction methods vary, depending primarily on operating temperatures. A simplified fuel cell* (**1**) *shows the essential characteristics, the anode-electrolyte-cathode sandwich, the paths of ions and electrons, and fuel and oxidant. Three major fuel cell concepts* (**2**) *are (left to right) low-temperature hydrogen-oxygen or alcohol devices, moderate-temperature hydrogen-oxygen, and high-temperature cells using molten carbonate electrolytes with a variety of fuels. One of the earliest fuel cell achievements* (**3**) *is the Union Carbide Consumers Products Co. hydrogen-oxygen battery, with carbon electrodes impregnated with noble metal catalysts.*



hour capacity, or about $2 per pound of weight.

High-temperature cells, if used industrially, must be maintained at their temperature regardless of load conditions. Under light load conditions, normal energy losses may not be sufficient to maintain temperature, and auxiliary heat must be supplied. Under high loads, heat generation may be excessive and cooling from an outside source may be required. A means for energy storage might be necessary to smooth out the peak loads.

Fuel cells also may find application in the domestic market. Natural-gas fuel cells in the home would take advantage of low-cost gas, and provide all electricity requirements of the home.

Most current efforts in civilian fuel cell applications involve propulsion of automobiles and other vehicles. It is not yet clear what type of cell is best suited for this purpose, or what type of fuel will have to be produced in quantity to meet the demand. At the moment, propane and methyl alcohol are good prospects because they are liquids and contain a lot of energy per unit of volume. And they may not be too expensive to produce.

The advantages of fuel cells for automobiles are lack of smoke and noise, few moving parts, less wear, and a more simplified automobile design. One conceptual design for a mass-produced car has been prepared by Brooks Stevens Associates, Milwaukee, and is based on the assumption that fuel cells can be housed within the wall thickness of the body shell.

An early return of electric cars has been predicted rather freely. If true, the advent of a fuel cell car will be speeded since the two would be similar technologically.

No radio interference

Fuel cell power supplies for military purposes are based on completely different concepts, since cost of operation is offset many times by special requirements of light weight, radio and radar silence, and lack of noise. Because the fuel cell has no moving parts, no noise is involved in its operation, in contrast with the standard combination of internal combustion engine and generator.

Lack of moving parts also results in total lack of radio interference that arises in commutators of conventional generators. Specialized cells, such as the hydrox cell operating at ambient temperature, also are advantageous because they do not produce the bright infrared image caused by the exhaust of an internal combustion or gas-turbine prime mover.

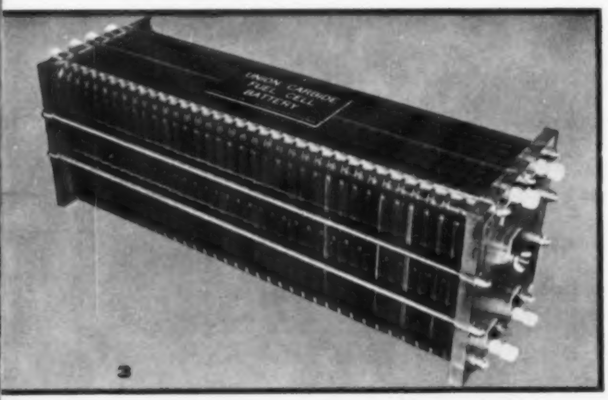
In space applications, high ratios of power to weight and volume are necessary and the fuel cell must function unattended in a zero-gravity field. In many cases, a cell must be regenerative so that a fixed charge of fuel or oxidant can be regenerated by energy from the sun, and reused in the cell.

The cell might be regenerated with electricity from silicon solar cells, or by using the sun's energy in photochemical reactions of fuel cell products. These requirements put a premium on ambient temperature operation and simplicity in design and function.

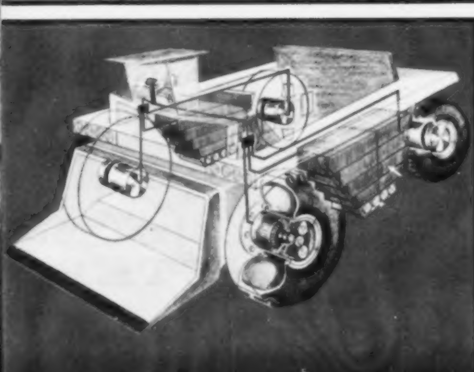
The success of hydrox cells

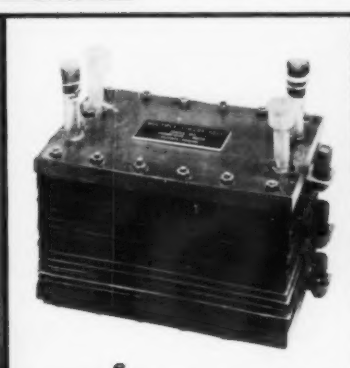
Of all fuel cells in laboratory or prototype stages, hydrox cells have the most successful history. The Bacon cell, conceived in England in the early 1930s, has been developed over the longest period. In spite of its elaborate pressure control requirements and other complexities, the Bacon cell is important because of its spectacular performance.

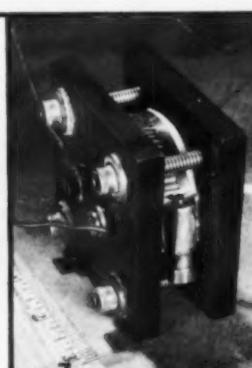
Current density (amperes per square foot of electrode area) is a measure of performance. The larger the current density, the more compact the device. The Bacon cell has been reported to give 500 to 1000 amperes per sq ft, several times any value reported by competing cells. Development of the Bacon concept is being carried out by the American



CELLS ARE STACKED *together in modules (**4**) in the Pratt & Whitney application of hydrox cells to vehicle secondary power systems. Allis-Chalmers Mfg. Co. engineers visualize the use of fuel cells to power future earthmovers (**5**). A plastic Fuelox fuel cell for hydrogen-bromine systems (**6**), developed by Ionics Inc., is capable of delivering about 35 watts of power. An experimental model of a lightweight regenerative fuel cell (**7**) is under development by Electro-Optical Systems Inc. General Electric's 200-watt portable fuel cell pack (**8**) developed for the Marine Corps weighs 30 lbs, takes the place of a 55-lb engine generator or 80 lbs of batteries, and can be handled easily by one man.*







licensees, Leesona-Moos and Pratt & Whitney Aircraft Div. of United Aircraft, East Hartford, Conn.

Closest in performance to the Bacon cell is the hydrox cell developed by National Carbon, now called Union Carbide Consumers Products Co., Parma, Ohio. A much simpler device, the Union Carbide cell operates at atmospheric pressure and low temperatures (100-160 F), and yields current densities of 100 to 300 amperes per sq ft. These cells powered the battery of lights at the Brussels World Fair in 1959.

A fuel cell developed by Allis-Chalmers, Milwaukee, is somewhat similar to the Union Carbide development in construction and operation, but uses metal electrodes. About 1,000 compact cells of this design were installed in a 20-hp electrically driven tractor now on display in the Smithsonian Institution, Washington, D.C.

Demonstration of the Allis-Chalmers tractor in late 1959 provided a great impetus to fuel cell developments in general. Even though it has not been confirmed that propane was utilized in the fuel mixture, the fuel cell tractor remains an important achievement in hydrox cells because of its simple construction and operation. It remains the largest-scale fuel cell power package ever demonstrated.

Recent activities with hydrox cells using caustic electrolytes have been on a much smaller scale. However, they indicate continuing improvements that should help this type of cell maintain its important position. Electro-Optical Systems Inc., Pasadena, Calif., has tested a cell that has porous nickel electrodes, with an aqueous caustic electrolyte held in the pores of an asbestos bed to keep the electrodes from becoming flooded with the solution.

An atmospheric-pressure hydrox cell that operates at 300 F to drive off product water as vapor has been studied by the Kettering Foundation, Yellow Springs, Ohio. A pasty mixture of hydroxides serves as electrolyte, and metal electrodes are used. The Kettering Foundation also has developed an acid cell operating at about the same conditions, but with phosphoric acid as the electrolyte. Inert powders are mixed with the acid to make it pasty.

Completely plastic fuel cells

Almost completely plastic fuel cells with ion-exchange membranes have been produced for hydrox systems by GE's Aircraft Accessory Turbine Dept., Lynn, Mass., and Ionics Inc., Cambridge, Mass., and for hydrogen-bromine systems by Ionics. This type of cell is almost ideal because the entire housing can be plastic and only the electrodes must be metallic powders, or screens capable of containing required catalysts. The ion-exchange membrane is a wet, pliable film similar to a solid electrolyte, with no orientation problems for spillage control.

The GE Turbine Dept. has developed a 200-watt, portable power pack of ion-exchange cells for the Marine Corps. Probably the most successful military fuel cell application to date, the pack can be used to generate power for portable radar units in the field. Air is the oxidant, and hydrogen fuel is produced as needed from reaction of a metal hydride with sulphuric acid.

Bromine, considered by Ionics to be superior to oxygen as an oxidant in regenerative fuel cell practice, is used in their low-temperature cation-exchange cell (Fuelox). Provision is made for regeneration of the bromine by current from silicon solar cells. Ionics also has developed a dual-membrane cell that uses two anion-exchange membranes with intervening aqueous caustic for hydrogen-oxygen systems.

Despite their success in recent years, ion-exchange cells have technical drawbacks, such as control of membrane moisture content, destruction of plastic membranes from local overheating, and scaleup beyond a fairly small size. Investment costs are high, largely because of high catalyst costs.

Alcohol, a breakthrough

Research on alcohol fuel cells has increased notably in the last few years. Three approaches, all at low or moderate temperatures, have been described: carbon diffusion electrodes and aqueous electrolytes; metal diffusion electrodes and anion-exchange membrane electrolytes; and alcohol dissolved directly in caustic electrolyte, with a non-diffusion anode and oxygen diffusion cathode.

The first two schemes were pioneered at the Signal Corps Research & Development Laboratory, Fort Monmouth, N.J. They use established hydrox fuel cell concepts but with liquid alcohol diffusing into the anode instead of gaseous hydrogen. While attainable current densities are modest, the concept represents a breakthrough in the direct utilization of liquid fuels at low temperature.

A third approach, called the dissolved-fuel or soluble-reactant fuel cell, utilizes higher current densities than the first two, and was initiated by Prof. E. Justi, of the Technical Institute, Braunschweig, Germany. Esso Research & Engineering Co., Linden, N.J., and Monsanto Chemical Co., Everett, Mass., also have been active in this approach.

Dissolved-fuel cells depart dramatically from conventional fuel technology by mixing fuel with the electrolyte and using a non-porous

As manager of energy and chemical conversion research, Dr. Eugene B. Shultz Jr. is in charge of fuel cell programs and basic studies on hydrogenation, pyrolysis, and gasification of fossil fuels at the Institute of Gas Technology. The author of numerous papers in this field, Dr. Shultz holds a PhD in chemical engineering from Illinois Institute of Technology. Co-author Dr. Egon A. De Zubay is a specialist in fuels and combustion, applied mechanics, heat transfer, and nuclear engineering research. Prior to joining Atlantic Research, he was affiliated with Curtis-Wright Corp. and Westinghouse. He received his ScD in mechanical engineering from Carnegie Tech.

 see page 40

anode. No reaction occurs except at the anode surface. A conventional oxygen diffusion cathode generally is used, but dissolved oxidants, such as hydrogen peroxide, may be substituted.

Methyl alcohol is the fuel that has been studied most, although some important experiments with hydrocarbons, such as ethane, at pressures up to 800 psi, have been reported by Esso. The Esso tests are the only successful attempts to use hydrocarbons at moderate temperatures (300 F and lower). Other laboratories or scientists investigating alcohol cells are Union Carbide Consumers Products; Prof. W. Vielstich of the University of Bonn, West Germany; the Institute Francais du Petrole, France; Allis-Chalmers; and California Research Corp., Richmond, Calif.

A drawback to all alcohol cells using caustic electrolytes is the reaction of carbon dioxide, a product of oxidation, with the electrolyte. A great need exists for electrolytes that will reject carbon dioxide. The electrolyte could be recycled to remove carbonates in external apparatus, but this is an inherently expensive approach. Use of acid electrolytes, which do not react with carbon dioxide, seems more likely.

Coal gasification products

In the last 10 years, feasibility of high-temperature molten carbonate fuel cells has been demonstrated for a variety of fuels. Three major projects have attempted to utilize hydrogen and carbon monoxide, products of coal gasification. The projects were carried out at the University of Amsterdam and the Central Technical Institute T.N.O., Netherlands; Sondes Place Research Institute, England; and Consolidation Coal Co. (formerly Pittsburgh-Consolidated Coal), Library, Pa.

Essentially three physical variations of molten carbonate cells are known: a molten electrolyte held in porous ceramic matrices; pasty mixtures of a molten electrolyte and inert filler; and a free molten electrolyte. In the latter case, dual-porosity sintered metal electrodes are needed to prevent electrode flooding.

Several patents integrating coal gasification processes with high-temperature fuel cells have been obtained by Dr. Everitt Gorin, Consolidation Coal Co. Objective is to balance heat requirements and losses between the steam-coal gasifier and the fuel cell mounted in contact with one another. Such a scheme might be used in a large-scale power generation unit, and could lead to higher efficiency of coal utilization than a conventional steam-turbogenerator plant.

A fourth molten carbonate fuel cell project, conducted at Curtiss-Wright Corp., Quehanna, Pa., concentrated on a propane-air fuel cell.

Natural-gas cells for homes

The Institute of Gas Technology, Chicago, under American Gas Assn. sponsorship, currently is developing high-temperature fuel cells to use natural gas. One goal is a power pack for home installation.

In most parts of the country, a

IDEAS AND APPLICATIONS #3

The Biochemical Fuel Cell

The biochemical fuel cell is an electrochemical generator of electrical power in which microorganisms are utilized to carry out the chemical reactions at one or both of the electrodes.

Any material, organic or inorganic, that can be utilized by a microorganism in its catabolic processes may be used as a source of electrical power. An electrode immersed in the products of metabolism will exhibit a voltage with respect to a standard electrode determined by the chemical species present.

The current produced is proportional to the rate of metabolism of microorganisms and the number of microorganisms taking part in the reaction, as well as the number of electrons released in the particular reaction.

Energy available from the reaction is less than that obtained in an ordinary fuel cell because the microorganisms use a portion of the energy for their own metabolic processes. However, microorganisms have an efficiency in the vicinity of 50%; approximately half of the energy available in an ordinary fuel cell will be available in a biochemical fuel cell.

On the other hand, the rate of metabolism of microorganisms indicates that biochemical fuel cells may produce more power than ordinary fuel cells. Also, biochemical fuel cells can utilize fuels that currently are considered waste products.

Scientists find biochemical fuel cells intriguing because they can utilize such fuels as cellulose, sugar, sea water, and even sewage. A biochemical system using these fuels may be designed to produce a product that would not be considered a nuisance.

For instance, wood pulp waste could be converted to carbon dioxide, water, and precipitated sulfur or sulfur compounds. Or raw wood pulp could be converted to glucose that can serve as a fuel for other biochemical fuel cell systems.

continued on next page

INDUSTRIAL RESEARCH, BEVERLY SHORES, IND.

unit of energy in the form of gas costs the residential consumer only one-sixth to one-tenth as much as a unit of energy in the form of electricity. If natural-gas cells can be perfected, basic costs would be reduced significantly. The low cost of transporting and distributing energy as gas to consumers' homes could provide the convenience and versatility of a single source of heat and electrical energy.

Development of improved molten carbonate cells for natural gas is in progress. Because of corrosion and decomposition, long-range studies on solid oxide electrolytes to replace molten carbonates are underway at the Gas Institute and the Ceramics Div. of Armour Research Foundation, Chicago.

Direct use of coal

Westinghouse Electric Co. Research Laboratories, Pittsburgh, has been investigating a novel fuel cell technique that may use coal directly without prior gasification to carbon monoxide, hydrogen, or methane. The device, still in the laboratory, is a high-temperature oxygen concentration cell.

Oxygen in ionized form is transferred through the electrolyte from cathode to anode, where the ions give up electrons, and combine to form oxygen gas again. Oxygen gas is removed quickly from the anode by reaction with a carbon rod protruding into the anode room. Carbon dioxide then is removed. The driving force is the oxygen concentration difference between cathode room and anode room.

The Westinghouse cell may develop into a device for central power generation from coal. Before this can happen, however, some difficult engineering problems must be overcome, particularly in coal handling. Schemes utilizing fluidized coal feeding may be useful.

'Exotic' military fuels

Exotic fuels and oxidants are under study for many special military and space applications. Most publicized is the sodium fuel cell invented by Prof. Ernest Yeager at Western Reserve University, Cleveland. Electrochemical reaction of sodium with water and oxygen is controlled by an amalgam of sodium in mercury.

A 75-kw prototype of a submarine power plant now is being engineered by M. W. Kellogg Co. Research & Development Laboratory, Jersey City, N.J., for the Navy's Bureau of Ships. Including fuel storage, it is expected to be about 15 times lighter than its equivalent in standard batteries. Another attraction is its high theoretical electromotive force of nearly 2 volts.

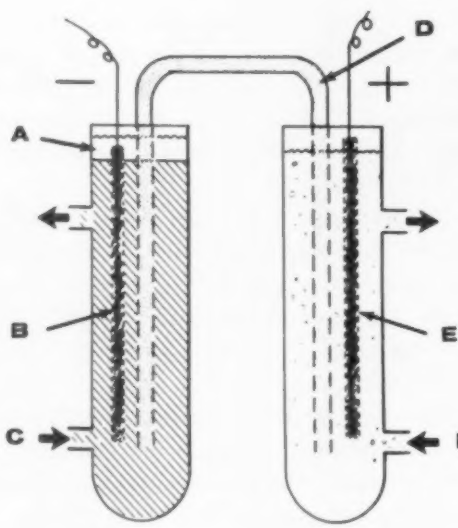
A similar development, by Hoffman Electronics Corp., Los Angeles, is a sodium cell that uses bromine as oxidant. A special feature of this cell is its ability to deliver a massive peak pulse as high as 4000 amperes per sq ft for 0.1 millisecond.

Magnesium-chlorine and zinc-chlorine cells, with sea water as electrolyte, have been studied by Dow Chemical Co., Midland, Mich., and a 20-cell zinc-chlorine fuel cell battery has been developed by Aerojet-General Corp., Azusa, Calif. Electric Storage Battery Co., Phil-

Dr. John A. Welsh, president of Flow Laboratories Inc., Arlington, Va., and Dr. Frederick D. Sisler, of the U.S. Dept. of the Interior Geological Survey, Washington, D.C., are two known developers of the biochemical fuel cell.

Sisler's prototype unit (see diagram) is composed of two sections containing inert electrodes—an anode section and a cathode section—separated by an ion-diffusion bridge. A mixture of sea water containing organic matter as fuel and bacterial cells (or enzymes) as a catalyst is placed in the anode section. The cathode section contains sea water and oxygen.

Essentially the energy released comes from bacteria "burning" the organic matter, but the cell design is such that the energy is released as electricity instead of heat. ■



THE BIOCHEMICAL FUEL CELL:
A—mineral oil seal,
B—electrode,
C—solution containing reductants, electrolytes, and catalysts,
D—KCL agar bridge,
E—electrode, and
F—solution containing oxidants and electrolytes.
The prototype unit shown is being developed
by research workers of the U.S. Geological Survey.

adelphia, has reported a zinc-oxygen fuel cell battery.

Hydrazine is another exotic fuel receiving recent attention. Monsanto scientists have been studying fuels that dissolve in caustic electrolytes to be reacted in their "soluble-reactant" fuel cell. Some of their best results have been obtained with hydrazine as the soluble fuel and hydrogen peroxide as the soluble oxidant.

Regenerative cells for space

In power systems for space vehicles, it is essential to use the sun as a primary source of energy. Conventional batteries are recharged with electricity from silicon solar cells. Fuel cells eventually may replace conventional batteries to obtain higher power per weight and power per volume ratios.

At least three hydrox cells are being adapted to regenerative operation, with hydrogen and oxygen being regenerated by electrolysis of the water formed in fuel cell operation. General Electric is using a cation-exchange membrane cell, and Pratt & Whitney is working on an aqueous caustic cell. In the latter case, separation of liquids and gases in gravity-free fields is difficult, so P & W is emphasizing development of a special vortex separator.

Electro-Optical's aqueous caustic cell differs in that the electrolyte is held by capillary forces in packed asbestos fibers. No difficulties in zero-gravity fields are claimed.

Since hydrox cells with cation-exchange membranes often show mediocre oxygen electrode performance, bromine was substituted for oxygen as the oxidant in the Ionics Inc. cation-exchange cell. Electricity from solar cells is used to regenerate bromine from hydrogen bromide, the product of electrochemical oxidation.

In some regenerative schemes, the hydrogen and oxidant are regenerated in the cell, which serves as both fuel cell and electrolyzer. Membrane degradation problems sometimes arise during the regeneration step when cation-exchange membranes are used as electrolytes. However, regenerative cells with ion-exchange membranes are far enough advanced to permit the first test in orbit. GE recently has obtained a contract to prepare a 30-day space test of two 50-watt fuel cell batteries.

A more direct approach to solar regeneration of fuel cells is to use photochemical effects of sunlight. Sunstrand Turbo Div. of Sunstrand Machine Tool Corp., Pacoima, Calif., is developing a cell that uses

nitric oxide as fuel and chlorine as oxidant. If exposed to light, nitrosyl chloride, a product of the operation, will break down into nitric oxide and chlorine, for reuse in the fuel cell. However, much engineering work remains before the process can be perfected.

Another photochemical scheme in an early stage of development at Lockheed Missiles and Space Div,. Sunnyvale, Calif., is a photosensitized redox cell which uses dyes that can be readily reduced in the presence of light.

The 'Redox' principle

Regenerative fuel cells are not limited to space applications. In some instances, it may appear desirable to regenerate a "chemical fuel" such as a stannous salt, from its oxidation product (a stannic salt) by reacting the stannic salt with a conventional fuel in a non-electrochemical reaction.

Thus, a conventional fuel such as coal, which is difficult to oxidize electrochemically, might be utilized indirectly. This is an example of a "redox," or chemically regenerative fuel cell. Although the redox principle is attractive, developers have found that engineering problems are formidable, and interest lags today.

An interesting concept that can be applied to any available source of heat is the thermally regenerative fuel cell. The chemical fuel and oxidant are regenerated from the oxidation product by heat. The complete cycle of power generation, followed by regeneration, constitutes a heat engine, and is limited by the Carnot efficiency. Projects in this field are limited to heat from nuclear reactors, but it is possible to use heat from combustion of fossil fuels, or heat from solar collectors.

Well-known thermally regenerative fuel cell developments by MSA Research Corp., Callery, Pa., and the Thompson Ramo Wooldridge Tapco Group, Cleveland, use nuclear heat with lithium as "fuel" and hydrogen as "oxidant." Electrolytes are molten lithium halides.

Two types of power plant probably will be sought: a space vehicle power pack for zero-gravity operation, and a larger-scale power plant for terrestrial application. Because gas-liquid separations ordinarily are effected by gravity, space applications certainly will pose a problem.

Double-skeleton catalyst

Recent projects are concerned with improving electrodes and electrolytes for fuel cells. One of the most novel disclosures is the "DSK" (double-skeleton catalyst) electrode invented by Prof. E. Justi in Germany. Patent rights are assigned to Ruhrchemie A.G., and Steinkohlen-Elektrizitat A.G.

The DSK electrode uses a microscopic supporting skeleton of sintered nickel containing a submicroscopic skeleton of disordered Raney metal, an active catalytic substance. Fabrication variations that permit unusually high current densities at low temperatures have been described for both hydrogen and oxygen.

Research on fuel cell electrode catalysis also is growing in importance. Engelhard Industries Inc., Newark, N.J., is studying noble metal catalysts to improve utilization of liquid organic fuels at low temperatures. Another long-term objective of investigators at Western Reserve, Worcester Polytechnic, Alfred University, and the Naval Research Laboratory, is to find catalysts that improve the performance of oxygen electrodes.

Carbon electrodes still are important, despite increased use of metal electrodes in recent years. Speer Carbon Co., Niagara Falls, N.Y.; Union Carbide Consumer Products; and the Signal Corps R&D Laboratory are working on this problem. Thin, flat carbon electrodes with better control over wet-proofing and carbon properties should be the outcome.

In all electrolytes operating below the boiling point of water, rejection of product water can be a problem. Union Carbide recently described a novel way to attack this problem. The diluted electrolyte solution is circulated to an outside vessel where a hydride is added to react with the water. Hydrogen is liberated for added fuel value, and a concentrated electrolyte solution is returned to the cell.

Fundamental studies to understand the action of molten carbonate electrolytes are underway by Prof. B. R. Sundheim, New York University, and Prof. G. J. Janz, Rensselaer Polytechnic. These projects may lead to improved electrolyte mixtures for high-temperature fuel cells.

The future of fuel cells in the spectrum of power conversion devices appears to be assured, even though cost, convenience, efficiency, and weight are not yet optimum. The basic background in electrochemistry has established the feasibility of a diversity of fuel cell concepts. The cells themselves will follow shortly. ■

HOW ADVANCED IS THE ART OF ENERGY CONVERSION?

Chemical–Electrical: Fuel Cells. The direct conversion of chemical energy to electrical energy via fuel cells has for years been regarded as a great potential power source. The problem has been to translate theory into practical, producible devices. Recent prototype testing indicates this need may now be met.

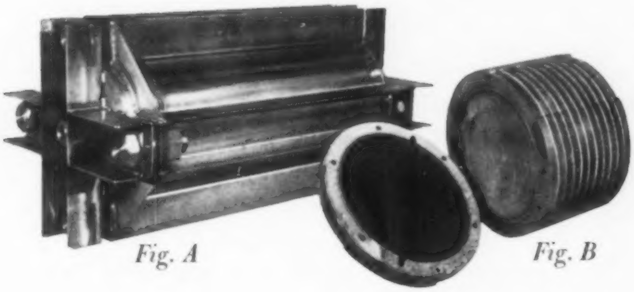


Fig. A *Fig. B*

■–The men at Leesona Moos Laboratories are responsible for a good deal of the early research on fuel cells. Present work is in two main areas: the hydrogen-oxygen Hydrox® cell, and hydrocarbon-air Carbox® cell. Thus far, prototypes of such cells have demonstrated good performance. Outputs with hydrogen equalling 150 watts per sq. ft. of electrode are readily achievable.

The Hydrox® cell can be designed as a regenerative unit which utilizes the same fuel and oxidant over and over, or as a non-regenerative unit which produces potable water as a by-product. The Carbox® cell, still under development, offers the advantage of more economical fuel.

■–*A typical Hydrox® Fuel Cell test battery is shown here. Fig. A shows the complete assembly and Fig. B indicates the internal fuel cell electrodes. It is but one of many configurations designed by Leesona Moos Laboratories.*

■–Leesona Moos Laboratories has been actively involved in the field of energy conversion for 13 years. Thermoelectric, electrochemical, and nuclear power sources, ranging from megawatt reactors to microwatt batteries, have been investigated. Some of these are offered as products, for example, the Dynox® solid state battery, Raypak® nuclear power pack, and Betachron® nuclear timer. An informative brochure on current state of energy conversion techniques with emphasis on fuel cells is available from Department 51.

LEESONA MOOS

LEESONA MOOS LABORATORIES

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when two materials are joined and heated, a potential difference results . . . the phenomenon is the basis for new heating, cooling, and power generation

THERMOELECTRI

■ THE FIRST OF STATIC energy converter techniques to move out of the laboratory, thermoelectricity is ready now to perform unique new military, industrial, and commercial functions, as well as to simplify existing problems.

Under development, for instance, are small-volume refrigerators for home, auto, boat, and plane use; devices for cooling electronic components, photomultipliers, and light fixtures; and large volume refrigerators for submarine air-conditioning. This is but a partial list of the many applications for thermoelectricity.

Little overlapping of applications will occur between thermoelectric and thermionic devices because of operating differences in the two principles. While the working fluid of both thermoelectricity and thermionics consists of electrons, the heated electrons in thermoelectric devices are emitted into a solid and thus operate at relatively low temperatures. In thermionics, heated electrons are emitted into a vacuum and such devices must operate at high temperatures.

In spite of enormous advances, thermoelectric devices are not yet ready to become competitive with steam turbine generating machinery and compressor refrigeration equipment. A proper balance first must be achieved between the factors influencing the economics and performance characteristics of thermoelectric devices before the full impact of thermoelectricity can be felt in industry.

How thermoelectricity works

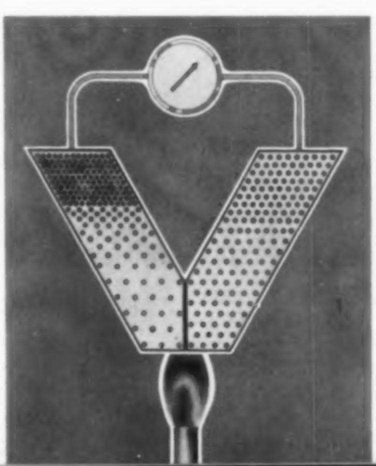
The principle underlying thermoelectricity is not new, but rather has been given new impetus as investigators gain new insights into thermoelectric effects. Basically, when two differing materials are joined, a contact difference of potential appears at the exposed terminals. The potential difference increases as the temperature of the joint increases, as compared to portions of the materials away from the joint. This fact was discovered more than 100 years ago and has been used extensively in thermocouples (chromel-alumel, for example) for temperature measurement.

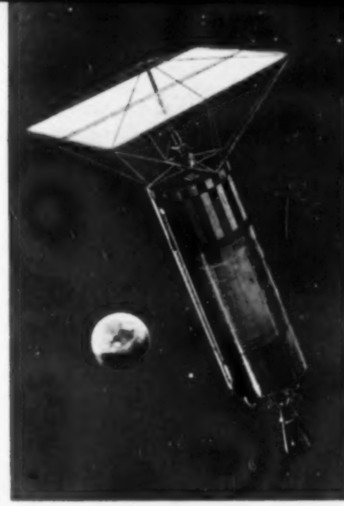
If the voltage is to be useful as a power source, the materials involved must be of low electrical resistance so that a high current can flow. For efficient generation of power, materials must have a high thermal resistance to minimize the heat that flows through the device without performing work. This combination of requirements is not fulfilled by either metals or insulators; only a special class of semiconductors of fairly recent origin (bismuth telluride, zinc antimonide, and germanium telluride) can qualify.

The same requirements hold for thermoelectric heat pumps where thermoelectric cooling particularly was impractical prior to the development of new materials.

Semiconductors offer another advantage in heat pumps since both positive (p) and negative (n) type materials are available. In an n-type material or a metal, when one end of the material is heated, electrons tend to migrate away from the heat and accumulate at the cold end to set up a difference of potential between the ends.

In a p-type material, holes migrate under the influence of heat and set up a potential of opposite polarity. If the thermocouple is formed by a junction of p and n materials, these two potentials add,





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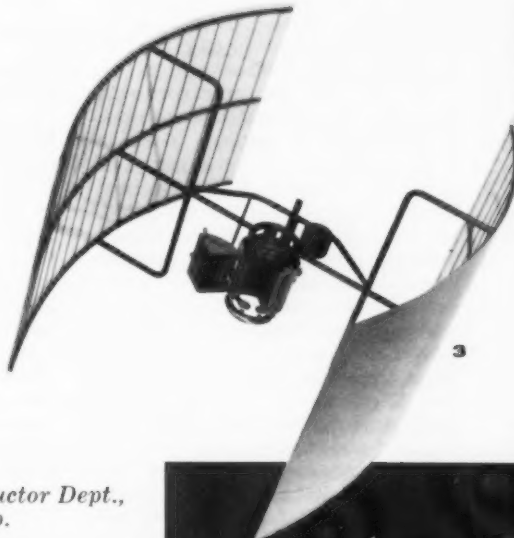

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by **Dr. W. B. Green,**
section manager, Semiconductor Dept., Westinghouse Electric Corp.

THERMOELECTRIC *generators obtain their power from Seebeck voltages produced by the redistribution of charges by temperature. Heat of the flame (***1***) causes the mobile charge carriers to move away from the hot junction. A thermoelectric backpack cooling unit (***2***) provides a constant temperature inside the protective suit. Heat of isotopic radiation in the space power supply model (***3***) is applied to tubular thermoelectric elements. A heat exchanger dissipates the heat. A new one kilowatt solar power thermoelectric generator for space vehicles operating near Mars (***4***) has been conceived by General Atomic engineers. The unit weights 80 lbs.*

As section manager, Dr. William B. Green is responsible for special product engineering at Westinghouse. He also is teaching electrical engineering at the University of Pittsburgh. A graduate of Johns Hopkins, Green received his PhD from MIT, where he was engaged in high voltage and insulation research.

making a larger voltage available than possible otherwise.

Since thermoelectric material inherently is of low electrical resistance, a device usually consists of a number of couples mounted between two heat sinks and connected electrically in series and thermally in parallel. To use this device as a heat pump, power is supplied to the couples and heat is pumped from one sink to the other. As a generator, heat is supplied to one sink and extracted from the other; power is generated by the couples.

Thermoelectricity offers the only static means of pumping heat, but a variety of other static power generators such as MHD (magnetohydrodynamics), thermionics, and fuel cells now are under study. At first glance, a competition whose outcome is not yet clear appears to exist. Quite the contrary is true, however. Each of these devices has unique features that lead to areas of application generally not overlapping.

For example, MHD operates at very high temperatures, thermionics at intermediate temperatures, and thermoelectrics at relatively low temperatures (presently to 1100 F). Fuel cells are limited at present to particular fuels, whereas thermoelectric generators use any heat source.

Any heat—any fuel

As you survey the spectrum of possible thermoelectric generator applications, the most striking single feature is the versatility resulting from the satisfactory utilization of any available heat source. Heat from the direct combustion of any fuel, from nuclear processes, or from the exhaust of some chemical or metallurgical process is equally applicable. (It is rumored that the Russians once offered an Arabian potentate a generator to be operated by the heat of burning camel dung.)

An example where conventional solutions are sufficiently undesirable that thermoelectric generation already is feasible is in corrosion control. Whenever a gas well casing or gas pipeline goes into the ground, an electrochemical reaction takes place. The metal pipe becomes one electrode in a battery; the dissolved minerals in the ground become the other electrode. A small current flows and with it move ionized atoms of the pipe materials. This movement, called galvanic corrosion, eventually leads to pipe failure and costly replacement.

The cure for galvanic corrosion is widely known and successful. A small voltage of opposite polarity is impressed between the pipe and carefully constructed ground bed. Thus galvanic voltage is cancelled, and corrosion stops. It is simple in principle, but difficult in practice when the casing or line is in an isolated location. In this situation, a transmission line from the nearest source of power can be installed to lower the voltage and rectify it to d-c. Alternatively, a motor-generator can be installed to supply the required power directly.

The former solution requires considerable capital; the latter, constant maintenance. But a thermoelectric generator in this application can be heated directly by the immediately available and inexpensive gas. Low voltage, low resistance output of the generator directly matches low resistance of the pipe-to-ground circuit.

Waste heat seems to offer limitless opportunities for exploitation. Take the jet plane for example. Immense quantities of heat pouring from jet engine exhaust perhaps could be used for thermoelectric generation of power required for lighting and air-conditioning the cabin. Ground supplies already handle the load until warm-up occurs. It doesn't matter that a thermoelectric device is compartively inefficient, because the heat is free. The only pertinent questions seem to be reliability and initial cost.

Generators already have been made to operate from natural gas, gasoline, fuel oil, istopes, nuclear fission (both inside and outside the reactor), and other waste heat. It is clear that many applications of thermoelectric generators will result from their adaptability to any fuel or any heat.

Static devices are quiet

Thermoelectric devices, whether heat pumps or power generators, are static in operation and therefore quiet. This quality is useful in many ways. Submarines, for example, often must wait nearly motionless with all sensors alert for the enemy. The power requirements for propulsion are small or nonexistent here; the load is required only for living and listening.

A thermoelectric power generator operating from boiling water in the reactor heat exchanger could supply this load readily. The noises of turbines and generator thus would disappear. It is probable that the materials and technology exist now to accomplish this operation.

Thermoelectric heat pumps are equally useful in a submarine since conventional air-conditioner compressors are a constant source of noise. A thermoelectric heat pump could air-condition a submarine readily, pumping heat from the ship and dumping it in the ocean. For operation in cold water, a reversed polarity input to the thermoelectric heat pump will remove heat from the ocean and use it to warm the heating system water in the boat. Again, materials and devices now are available to provide operation in performance, in many instances, to the compressor.

In 1955, the Navy and Westinghouse jointly funded a large-scale project to develop thermoelectric materials with efficiencies adequate

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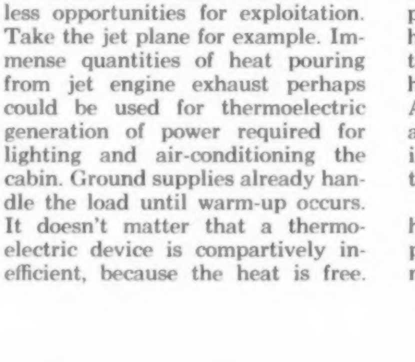

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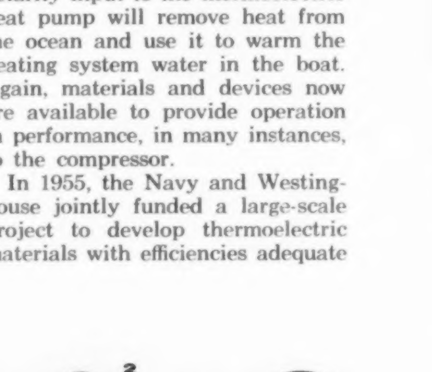

to perform the required operations. One of the results of the program was a five-kilowatt propulsion power supply prototype. Delivered in 1960, it is the largest thermoelectric generator built to date.

Static devices do not wear out

The lack of moving parts means no wear, no maintenance, and long life. Static devices in marker buoys already are saving a great amount of money for the Coast Guard. To do maintenance work on a buoy, which may be 30 ft tall and weigh several tons, a tender must hoist it from the water and return it to port. The cost and difficulty of the operation argue strongly for a major effort to minimize maintenance.

The light systems on the newer buoys are battery-powered blinkers. With finite battery life and high maintenance costs, this system produces electricity at \$8 to \$9 per kilowatt hour. A thermoelectric generator burning propane gas could charge these batteries constantly. A generator operating with only a 2% overall efficiency from fuel to power could be expected to cut power costs to about \$1.50 per kilowatt hour. Such devices are now feasible. An even more impressive improvement will result when low-cost isotopes are available to supply a long-lived source of heat.

As NASA and the Air Force extend their space programs to more sophisticated satellites and rockets, the problem of a power source becomes ever more acute. Reliable, long-lived operation is just the beginning; here, weight and ability to operate free of gravity also are prime considerations. Solar cells adequate for small orbiting vehicles would fail in the black of a lunar night and require too much space for the larger vehicles anticipated in the future.

The heat source, by common agreement, will be nuclear. Small devices will have radioisotope sources, and large units will operate from small reactors using sodium, potassium, or sulfur in the heat exchanger loops.

Temperatures supplied by these sources indicate that presently available thermoelectric materials should suffice. The high efficiencies desired eventually may lead to thermionic-thermoelectric combined units where the higher temperature thermionic device supplies its exhaust heat to a thermoelectric device.

A typical power supply will consist of a small nuclear reactor centrally located within the spaceship. The reactor will heat liquid sodium flowing in a heat exchanger loop. Outside the reactor (at a temperature of perhaps 1100 F), the sodium will pass through thermoelectric modules and then back into the reactor. After flowing through the thermoelectric material, the heat will be exhausted into a second liquid loop at perhaps 575 F. The second liquid loop will pass into a radiator assembly made as an integral part of the vehicle's skin. This skin will lose heat to the external vacuum solely by radiation.

Such systems become desirable when about 100 watts of power are required, and probably are mandatory above a few hundred watts. It seems unlikely that thermionic systems will be available soon or that electromechanical systems will have the desired reliability. In view of this, thermoelectric systems appear to be an almost certain choice.

One final characteristic of thermoelectric generators makes them promising for both Army and civilian uses. A single thermocouple has an output determined by its size, material, and operating temperature. Characteristically, the current will be several amperes while the voltage will be less than one-tenth of a volt. A generator consists of a number of these in series, with the number determined by the load anticipated. Output may range from milliwatts to kilowatts of d-c power.

Static inverters using semiconductor devices can change the d-c to a-c with very high (85 to 95%) efficiency. In many applications where a small amount of portable power is required, only a gasoline engine-generator set now can be used. A small propane-fired thermoelectric unit would be both lighter and quieter. The Army sees such a device as an ideal front-line communication power supply. Comparable civilian uses for portable, emergency, or remote applications are easy to imagine.

Cold in small packages

Man has known how to generate cold in a controlled manner for many years. The most popular refrigeration method uses a motor-driven compressor operating in an evaporative-type closed liquid loop. But for many applications—cooling of electronic components, for example—the size, weight, and noise of the compressor have made its use undesirable.

The typical thermoelectric heat pump is remarkably simple. It consists of a series of thermoelectric junctions attached on one side to a cold surface and on the other side to a heat sink. The junctions require only a relatively pure d-c current for operation.

Because of this simplicity and potential applications for small amounts of cold, you would think there would be an unprecedented rush to use this new device. Curiously, it now seems that among new solid state devices, thermoelectric heat pumps will take an unusually long time to win acceptance.

The explanation is simply that while a ready market existed for transistors among tube users, no small amount of cold in useful form

SUB-GENERATOR *(1) by Westinghouse powers largest thermoelectric generator ever built. Pesco Products' thermoelectric micro-refrigerator (2) cools electronic components. Bottle water cooler (3), built by Westinghouse, is the first consumer application of thermoelectricity. Spot cooling thermoelectric devices (4) are useful for transistor temperature control.*

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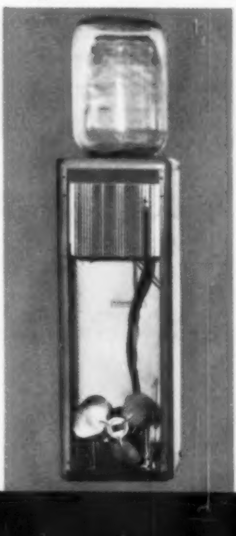

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existed before. Thus no easy replacement market now exists for thermoelectric cooling. Entirely new concepts must be formulated in the minds of engineers previously unacquainted with electronic cold.

Keeping components cool

One of the most useful of the new concepts is spot cooling. In many complicated assemblies of components, one or a small number of components will have characteristics or reliability that are affected adversely by operating temperatures satisfactory to the rest of the components.

An example is the germanium transistor, whose characteristics deteriorate rapidly above 175 F and reliability becomes very poor. A limitation of 175 F is not serious to most consumer and industrial products, but in many military applications, weight and space can be saved by allowing temperatures above 200 F.

A thermoelectric spot cooling heat pump will remedy the situation. The transistor involved can be thermally isolated and its temperature lowered below the surrounding ambient. The circuit function then is unaffected by a high ambient.

The spot cooling heat pump is like any other heat pump because it moves heat from the cold surface to a heat sink which dissipates heat to the ambient. Power is required to cause the pump to operate; this power, as heat, also is passed on to the heat sink. For a small expenditure of power, we have achieved the ability to cool any particular crucial spot below its surrounding ambient.

An extension of this principle is illustrated in an application made by GPL Div., General Precision Inc., Pleasantville, N.Y., when faced with the problem of building a closed-circuit television system to operate in a high temperature ambient. The ambient temperature was too high for the operation of the camera vidicon tube; thus, simple blower air cooling was of no value. A thermoelectric heat pump in the form of a yoke was mounted around the tube and reduced the temperature of the critical area to a safe value. The use of a compressor or absorption system in this instance would have been impractical.

A true heat pump is entirely reversible: reverse the motive force and the direction of heat flow reverses. For a thermoelectric heat pump this means reversing the polarity of the input d-c power. Since polarity reversal can be handled with precision by an electronic circuit, another sort of device becomes feasible.

A quartz crystal used as a frequency reference oscillator control must be kept at a constant temperature to be stable in frequency. The present method is to mount the crystal in an oven and keep the temperature above the maximum that the surrounding ambient will attain, usually 195 F. It would be better from the point of view of crystal aging if the temperature were below room temperature, for example 50 F.

A thermoelectric heat pump makes this quite reasonable. When the surrounding ambient is above 50 F, the heat pump cools the crystal. When the ambient is below 50 F, the pump heats the crystal. A similar device has performed well from minus 75 to 195 F.

The amount of heat that can be moved by such a heat pump depends primarily on the amount of semiconductor material and how it is distributed. As a result, capacity in the unit can be designed to match exactly the load to which it will be applied. This design capability is in contrast to compressors where only a few standards usually are made for economic reasons, and where no really small sizes are available. A result of this capability is that economies will become possible, particularly for small refrigerated consumer products.

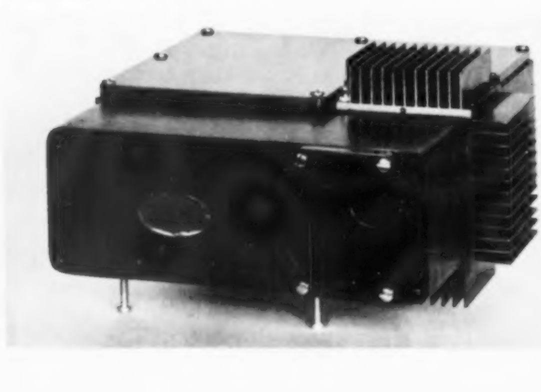
The price pattern of new developments

The introduction of new semiconductor devices to the public follows a pattern now taking shape in the thermoelectric field. Unit cost initially is high. As time advances and volume increases, prices decline. As volume increases, prices reach a bottom determined by the cost of minimum essential materials and labor. Here the price remains until and unless major technological advances occur.

A commentary on our times is that at the introduction of a new development when the prices are highest, the primary market is military and the performance of an essential function often makes price immaterial. A quiet submarine air conditioner or a satellite power supply, for example, have substantial military importance.

The real possibility of a war in which nuclear, biological, or chemical weapons would be used has led to work aimed at the survival of troops in devastated areas. Any of the three forms of warfare will de-

FOUR THERMOELECTRIC *generator modules surround the shell of a gas furnace manufactured by C. A. Olson (left) to supply the 130 watts necessary to operate the furnace blower. General Precision's closed circuit TV camera (below) incorporates a heat pump to maintain low operating temperatures for satisfactory operation.*



mand that soldiers function in a carefully purified atmosphere equally well in tropic or arctic weather.

To resolve this problem, a thermoelectric survival suit, made of lightweight but impermeable material that offers some protection against chemicals or radioactive dust, has been developed. The air supply, provided through a filtered intake, can be heated or cooled in a variety of ways. A simple gas burner can warm the air inside the suit with a thermoelectric generator supplying power to drive a circulating fan. Or a battery-powered thermoelectric heat pump and fan either heat or cool the air inside the suit, depending on the polarity of applied power. An identical sort of system for atmosphere control can be applied to inflatable structures and to vehicles with equal success.

In the next lower price bracket are industrial projects, where the ability to achieve something unique allows a product to command a price otherwise unjustified. The advantages of thermoelectric devices for cathode protection, for example, are so obvious, that when coupled with low fuel costs, an assured market is inevitable. Prevailing prices soon will be low enough for this market, and prototype units already are being examined in the field.

Uniqueness influences cost

Consumer products possessing the same unique features also may command a price adequate to allow fairly early use of new devices. Modern outdoor living is an example of an area where the unique feature possessed only by thermoelectricity can be applied to a large market.

A useful consumer device would be a small portable refrigerator and oven. A demonstration device for thermoelectricity has been built in the form of a hostess cart, incorporating both an oven and a refrigerator. The oven is a small, conventionally heated model designed primarily to keep prepared dishes warm. The refrigerator is cooled by a thermoelectric heat pump.

The hostess cart exemplifies the unique type of product for which thermoelectricity now is searching. The refrigerating function previously could not have been performed in such a compact portable form. While the finished product will not have a mass market, it commands a market wide enough and price high enough to assure success. From another point of view, it serves both to increase volume in an item whose

price is volume sensitive and to educate the public to the existence and potential of thermoelectric heat pumps.

Another novel product, made possible only by thermoelectricity and entirely feasible with today's techniques, is a bathroom heater developed by the Lone Star Gas Co., Dallas.

One of the disadvantages of gas-fired radiant heaters for bathrooms is their reliance on radiation to spread the heat. A possibility exists that the heat will not reach effectively within areas obstructed from direct view of the heater. Even a small blower to move the warmed air around the room would add immensely to the heater's efficiency and economy of operation.

The prototype developed by Lone Star resolves this problem thermoelectrically. The blower-driven cool air passes first over the cold side of a series of thermoelectric junctions, then past the gas burner and into the room. The hot sides of the thermoelectric junctions also face the burner and are heated by it. The power output of the couples drives the fan.

The future: lower cost, more uses

Prospects for thermoelectricity are as large or as small as the potential market. A substantial military market exists, but hardly large enough to justify the attention of the great number of companies not entering the field. The substantial industrial market will require lower prices than currently exist to achieve full potential volume. Finally, if prices fall drastically, a very large consumer market will become available. It is this last market which remains to be examined.

Among gas appliances now available, many require some electrical connection in addition to their gas supply. The gas clothes dryer has an electric motor rotating the clothes basket and the gas furnace has a blower driven by an electric motor. Two reasons exist to eliminate these external connections. First, it would be a substantial psychological boost and an economy to the contractor if his "all-gas" house had fewer electrical connections. Second, in the case of the furnace, a blower powered by a self-contained power source would operate even if an electrical failure occurred, as in a hurricane-hit area for example. A storm-proof furnace would have important sales advantages.

The C. A. Olsen Manufacturing Co., Elyria, Ohio, recently equipped a standard gas furnace with thermoelectric generators to power the blower motor. The thermoelectric generators were mounted directly on the shell of the combustion chamber. Flame heat provided the high temperature, and incoming air, passing into the furnace to be warmed, served to keep the low temperature fins relatively cool.

When the furnace burner comes on, the generators heat, until finally they are hot enough to supply just enough power to start the blower turning and moving a small volume of warm air. As temperature rises, the generator output increases and the amount of air moved by the blower increases, but the air temperature stays essentially constant. Similarly, on shutdown, air flow decreases as furnace temperature declines to maintain reasonably constant air temperature. This form of modulated air flow is another plus value added to the independence gained from external power.

Your November issue will begin a special series of articles on selling research to the government.

Housewives already have indicated their unwillingness to pay extra for scientific marvels that do no more than present appliances. So to be realistic, the thermoelectric device must replace the compressor for the same or lower cost. At current prices, one Btu of heat may be pumped in a refrigerator for $1 to $3 by thermoelectric means, not including the power supply. To realize a large refrigerator market, the heat pump, including power supply, probably will need to sell for about 10 cents or less per Btu.

The message is clear. A reduction of price by a factor of 50 to 100 to one is mandatory for full market exploitation. The future of thermoelectrics is inextricably bound up with these unprecedented price cuts. Will they occur? There is no clear answer, but the lines of attack now are obvious.

New and improved materials are very desirable and will relieve the problem if realized, but no one now associated with materials work can visualize a hundredfold improvement in this area. It is more likely that improvement in manufacturing techniques will allow a reduction in labor costs and will stretch the amount of work that can be done by a given quantity of present materials. ■

THE RESEARCH TRENDLETTER

October, 1961

Dear Sir:

Concentrated efforts to discover and develop new energy conversion schemes--the theme of this entire special issue of Industrial Research--have led to the investigation of hundreds of processes. And the search for new methods of meeting the immediate demands of future space travelers and commercial and industrial power requirements is expected to continue unabated.

Frontrunners in the energy conversion field appear to be thermoelectrics, thermionics, fuel cells, and magnetohydrodynamics (MHD), with fuel cells representing the most advanced state of product development.

fuel cells

A regenerative fuel cell, with efficiencies claimed to exceed 50%, has been developed by scientists at Armour Research Foundation, Technology Center, Chicago 16. Using a prepackaged chemical system, the cell can be transported easily to remote areas of the globe or launched to future manned space stations. The ARF system uses liquid electrodes to provide a constant conversion of heat energy to electricity. Spent chemicals are regenerated while hot chemicals are being discharged and decomposed to give electricity.

Electric Storage Battery Co.'s Exide Industrial Div., 2 Penn Center, Philadelphia 2, has demonstrated a model of a fuel cell-powered futuristic monorail system as a possible application of fuel cell power sources that are part of a long-range development program. An operating model of a fuel cell-powered midget automobile and the first full-size fuel cell developed experimentally for electric industrial material handling trucks also were revealed.

An entirely new concept in electrode design for fuel cells has been developed by Yardney Electric Corp., 40-50 Leonard St., New York 13. The concept involves the use of electrodes treated with radioactive isotopes to provide an impressive decrease in polarization as compared with untreated electrodes. An extremely flexible plate design may be developed, according to Yardney investigators. The use of oxygen electrodes made of sintered porous silver would permit the construction of a simplified cell design resistant to environmental stresses.

Important commercial and military applications are promised by the Fuelox cell developed by Ionics Inc., 152 Sixth St., Cambridge 42, Mass. The cell has demonstrated high power output of 40 watts per pound and is said to be capable of up to 10 times this output. The lightweight fuel cell is being developed to generate electric power in satellites and space vehicles under a $49,381 contract awarded by the Electronic Systems Div., U.S. Air Force Systems Command.

thermoelectric generators

The first thermoelectric generator made of ceramics has been developed for the U.S. Army by Minneapolis-Honeywell Regulator Co., 2747 Fourth Av., S., Minneapolis. (See photograph No. **1**.) Capable of operating at unusually high temperatures--up to 2400 F, the unit produces four times the voltage of the more common intermetallic thermoelectric generator. A pilot model delivered to the Army's Picatinny Arsenal, Dover, N.J., is designed to deliver 100 volts under no load.

The generator is made like a 14-layer cake, with nickel oxide sprayed on one side of each layer, and platinum on the other. Use of nickel oxide permits operation of hot and cold junctions at higher than normal temperatures. The resistance of the thermopile therefore is reduced and appreciable currents are supplied.

solar energy

The entire power conversion system for the Ranger Lunar Spacecraft, which on Aug. 23 went into an orbit hugging the earth instead of the hoped for elongated, egg-shaped orbit, is performed by nine modules 8 by 8 by 2 in. each in size. Developed by ITT's Industrial Products Div., San Fernando, Calif., the system includes a synchronizing generator containing more than 300 miniature components with about 1,000 different connections. The Ranger was designed to operate from power supplied by the sun and a 125-lb silver zinc battery. The battery provides power to run the spacecraft prior to acquisition of adequate energy from the 8,680-celled solar panels, and acts as a backup source to the solar supply when the craft is deep in space.

A prototype of a small self-contained electric power plant and pumping unit capable of improving the standard of living in underdeveloped areas of the world has been built by Westinghouse Electric Corp., 30 Gateway Center, Pittsburgh, in cooperation with the University of Wisconsin's Solar Energy Laboratory, Madison. (See photograph No. **2**.) A 50-watt power plant that converts the heat of sunlight into electricity by means of a thermoelectric generator, the unit uses an 8-ft parabolic mirror to gather sunlight and focus it on the thermoelectric generator containing 72 thermocouples. A larger solar-thermoelectric generator system, now under development, has been operated at part power. This unit will have a capability of up to 200 watts of electric power.

A $79,800 Air Force contract to continue the development of a unique solar energy converter for the Aeronautical Systems Div., Wright-Patterson AFB, Ohio, has been awarded to National Research Corp., 70 Memorial Dr., Cambridge 42, Mass. The new conversion technique offers possibilities of substantial weight reductions over conventional silicon cell systems now in use.

The Boeing Co., Seattle, is testing silver-cadmium cells for integration into a system concept for a satellite power package. Developed by Yardney Electric Corp., the cells are undergoing evaluation as replacements for nickel-cadmium batteries in solar cell accessory power systems. They are expected to allow operation at greater depths of discharge and higher charging rates than previously feasible, for important weight savings.

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A solar-powered Stirling-cycle engine that uses air as the working fluid was displayed at the recent United Nations Conference on New Power Sources by Battelle Memorial Institute, 505 King St., Columbus 1. The sun's rays can be focused by a mirror through a quartz dome on top of the cylinder to heat the air inside. As the air expands, it forces down a piston which turns a crankshaft. Battelle scientists now are working on a regenerative-type engine.

magnetohydrodynamics

Ceramics, rather than iron and steel, have been shown by Westinghouse scientists to be the best substances discovered so far for holding in check the high temperatures gases from which electric power is obtained in MHD generators. An experimental generator, with ceramic-lined walls, was operated continuously for a record 50 minutes. Usual operating period for such generators is only a few seconds.

Although the problem of long-time, large-scale MHD power generation is yet to be solved, the ceramic materials studied by Westinghouse are the first step toward the kinds of materials that may make MHD power feasible. In the tests, magnesium oxide performed the best and zirconium oxide showed good endurance.

thermionics

A flame-heated thermionic generator that burns a mixture of propane and air has been developed by Atomics International, a division of North American Aviation Inc., Canoga Park, Calif. The first time that conventional fuels have been used successfully to obtain the higher temperature required to operate an efficient thermionic converter, the device demonstrates the feasibility of developing compact, lightweight, silent power systems for a variety of practical applications.

Another pioneering concept in the interpretation of practical scientific advances—the RESEARCH TRENDLETTER WEEKLY—will be published as the result of a continuing, three-year demand by readers of the Trendletter section in this magazine.

If you are among I•R readers who have found the Trendletter section useful, you will be interested in our plans for expansion and development of the Trendletter into a weekly service.

When publication begins this winter, the weekly Trendletter will replace the monthly section in Industrial Research. The weekly Trendletter will be similar to the section in the magazine, but in addition will:

- Keep you appraised of your competitor's latest developments.
- Relate news of defense and industrial contracts to their possible impact on your company and on the stock market.
- Present applications of research in product development *weeks* before they appear in the technical press.
- Point up trends in scientific research and technical advancement.
- Describe what acceptance a new development is likely to have, and what project or process it might render obsolete.
- Provide an idea file (three-ring punched) complete with source information for detailed reference.

The Research Trendletter Weekly will do all these things every seven days—arriving *air mail* with Tuesday's development news the morning of every Wednesday.

Your time is your most valuable business asset and working tool. The Research Trendletter Weekly, which will carry no advertising, is designed specifically to conserve the time of management men responsible for the results of industrial research and for R&D investment. Written on Monday and Tuesday, it will be sent to you *air mail* to arrive on your desk each Wednesday morning—52 times a year.

WE

The Trendletter's new emphasis will be on *speed* of reporting. You will *regularly* have news of new scientific accomplishment six to eight weeks before it appears in the press.

The Research Trendletter Weekly also will emphasize the *profitability of research*, the competition in research projects, trends in research and development, and the interrelationship of science and marketing. It will report military and industrial contracts and their effects on your firm and on the stock market.

How will the Research Trendletter Weekly accomplish all this?

N

The weekly Trendletter will be a national weekly technical service—the only one affiliated with Industrial Research, the first and only technical magazine for management. By virtue of this close connection—this day-in, day-out working contact with Industrial Research editors, consultants, technical analysts, and the famous Industrial Research Editorial Advisory Board—the Trendletter will furnish you with a unique scientific-management reporting service.

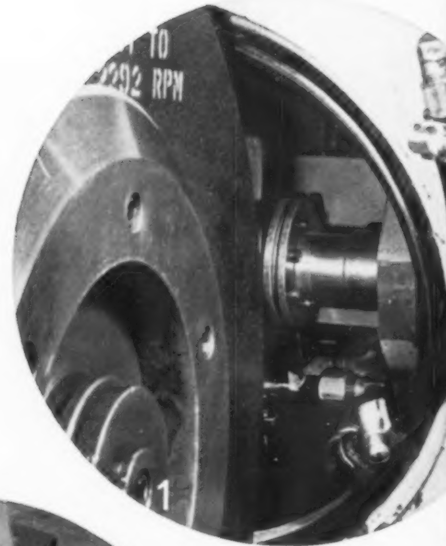
As a reader of Industrial Research magazine, we invite you to do this:

1. *Consider* what you want out of a national weekly service providing you with useful, practical scientific information.
2. *Read* the Research Trendletter section in this or any other issue of Industrial Research to see how such information would be of use to you if presented as a weekly, air mailed letter, containing the significant accomplishments of research *before* they appear *anywhere else*.
3. *Compare* the uniqueness of this service with any other financial, technical, management, or engineering service costing up to $150 or more.

After you do that, you probably will want to take us up on our Charter Subscription Offer at the special reduced pre-publication rates.

Here is our Special Pre-Publication Offer: as a Charter Subscriber, you will receive the Research Trendletter Weekly at $50 annually—a savings of $25 a year over the regular price of $75. (It's tax deductible if your firm does not pay the subscription cost.) We cannot repeat this offer after publication begins.

Later, next winter, after you begin receiving the Trendletter each week, if you do not find it is the most helpful service that money can buy, simply return the issues received with a note giving us your honest opinion, and we will return your full payment.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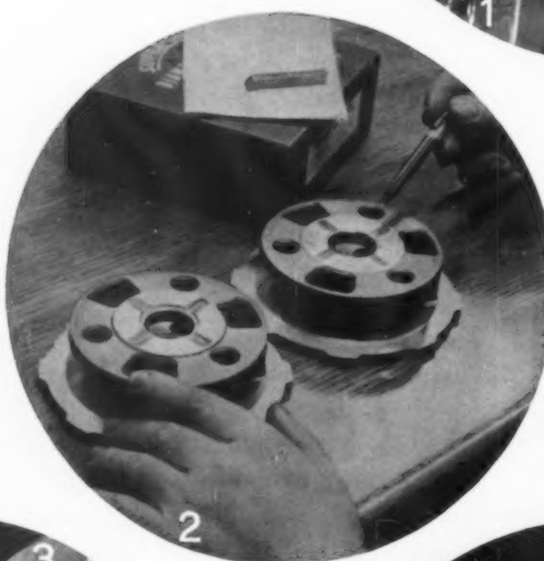
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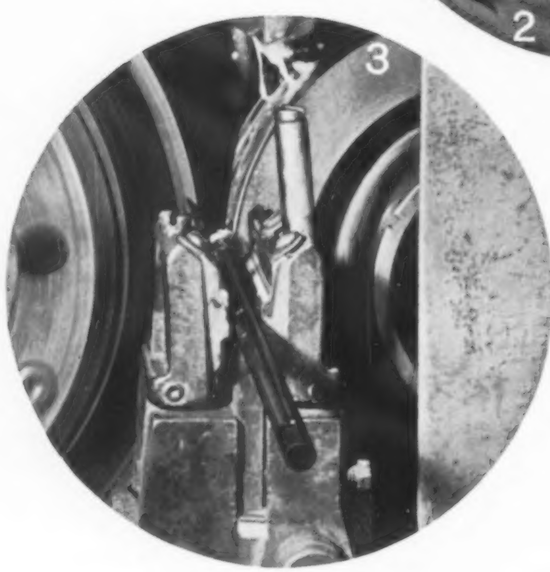
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electrical ion engines

The electrical (or electrostatic) ion engine will be given its first space test late in 1962, according to the National Aeronautics & Space Administration. RCA's Astro-Electronics Products Div., Princeton, N.J., is designing and building seven capsules to be used in ground and space tests by NASA. Cesium-fueled and mercury-fueled ion engines are being developed by Hughes Aircraft Co., Los Angeles, and NASA's Lewis Research Center, Cleveland. Advantages of the ion engine over chemical jet engines are small size, low fuel consumption, and the capability of being reignited at any time while in flight.

Methods for controlling and measuring the amount of cesium used in an ion propulsion engine for spacecraft are being studied by Dresser Industries Inc., Dallas 1, under a contract awarded by NASA.

Current production of cesium in the U.S. is only a few hundred pounds, but steady growth is predicted. Cesium in exceptionally high purity of over 99.9% now is available from The Dow Chemical Co., Midland, Mich. Used in ion propulsion and thermionic converters, the cesium is being produced through a metal-reduction process with a production capacity of several pounds a day.

A prototype of an advanced cesium ion engine, largest of its type, has been demonstrated by Electro-Optical Systems Inc., 125 N. Vinedo Av., Pasadena, Calif. (Photo No. **3**.) Capable of generating three-thousandths of a pound of thrust, the 61 beam, contact cesium ion engine has been operated in a large vacuum chamber up to 175 consecutive hours with no failures. The engine produced specific impulses in the 5,000 to 8,000-second range and efficiencies as high as 65%. The low thrust engines are a more advantageous propulsive means than chemical rockets and may be used as sustainers for the propulsive control and guidance of satellites.

gas turbines

A power pack with a 200-hp gas turbine engine has been developed by Martin Orlando, Fla., to provide all missile utility support requirements for the Pershing, a lightweight missile readily transported to sites where it can be erected and fired in a matter of minutes. The turbine engine, designed by the AiResearch Div. of The Garrett Corp., Phoenix, drives through gear pads, a 40 kva a-c generator, a 3,000 psi air compressor, and an air cycle air conditioner.

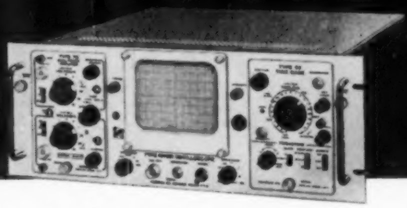
now low-cost Tektronix Oscilloscopes with 5-inch CRT's ...require only 7 inches of standard rack height

Tektronix Type RM561

A new, rack-mount, laboratory oscilloscope—basically an Indicator which accepts a wide range of plug-in units in both channels—the Type RM561 offers the type and degree of performance demanded for particular applications in the dc-to-4 mc region.

Indicator Unit ...... f.o.b. factory* **$450.00**

(without plug-in units—which range from $50 for a basic amplifier to $250 for the versatile dual-trace unit.)



Besides the 5-inch rectangular crt, other features of the Indicator Unit include: 3.5 KV accelerating potential, 8 cm by 10 cm viewing area, Z-axis input, 6 calibrated square-wave voltages from 1 mv to 100 volts (available at the front panel), regulated dc heater voltage thru separate regulator circuitry, regulated dc supply—which operates between 105 to 125 volts or 210 to 250 volts, 50-60 cycles to provide 85 watts of power for the plug-in units.

The plug-in units drive the crt deflection plates directly, house approximately ⅔ of the circuitry, contain minimum components and controls.

Eight plug-in units are presently available. These include two time-base units—one with 21 calibrated sweep rates from 1 μsec/cm to 5 sec/cm, 5X magnifier, extremely adaptable triggering facilities, external input to sweep amplifier, 1 v/cm sensitivity—and also six signal-amplifier units. The signal-amplifier units range from basic units (with passband from dc to 400 kc at maximum sensitivity, sensitivity approximately 1 v/cm with attenuation provided by variable potentiometer at the input) to more complex units including those for differential-input, dual-trace, and wide-band applications.

In addition, plug-in units under development include those for pulse-sampling, four-trace work, high-gain measurements, strain-gage and other transducer applications.

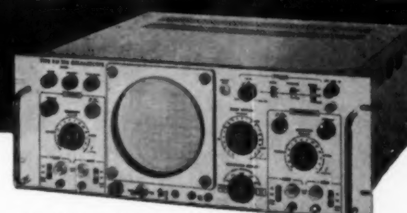
You can even design your own circuitry into skeleton units available.

Tektronix Type RM503

A new, complete-unit, rack-mount oscilloscope, the Type RM503 features practically identical horizontal and vertical amplifiers, 21 calibrated sweeps, five degrees of sweep magnification, extremely adaptable triggering facilities.

A differential-input X-Y Oscilloscope, the Type RM503 ideally suits curve-plotting applications using the X-Y method of operation, as well as most other laboratory applications in the dc-to-450 kc region.

Type RM503 ..... f.o.b. factory **$640**



Vertical and Horizontal Amplifiers
Frequency Response—dc to 450 kc (at 3 db down).
Sensitivity—1 mv/cm to 20 v/cm in 14 calibrated steps, variable uncalibrated from 1 mv/cm to 50 v/cm.
Differential input and constant input impedance at all attenuator settings.

Sweep Range and Magnification
Linear Sweeps—1 μsec/cm to 5 sec/cm in 21 calibrated rates, variable uncalibrated from 1 μsec/cm to 12 sec/cm.
Sweep Magnification—2, 5, 10, 20, or 50 times.

Triggering Facilities
Fully automatic, recurrent, or amplitude-level selection on rising or falling slope of signal, with AC or DC coupling, internal, external, or line.

Tektronix Cathode-Ray Tube
5-inch crt at 3KV accelerating potential provides bright trace on 8 cm by 10 cm viewing area.

Amplitude Calibrator
500 mv and 5 mv peak-to-peak square-wave voltages available.

Regulated Power Supplies
All critical dc voltages—and the input-stage heaters of both amplifiers—are electronically regulated.

For a demonstration of either of these versatile low-cost rack-mount oscilloscopes, please call your Tektronix Field Engineer.

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Where no metal but Platinum

Electrodes made of Platinum metal alloy deliver longer, trouble-free service in aircraft spark plugs

A spark plug fires an average of 1100 times per minute at cruising speed in a piston-engine airliner. With each vital spark, the ignited gasoline in the engine's combustion chamber heats the electrodes to high temperatures.

To withstand the rapid, repeated heating and cooling with every cycle of the engine—and to resist electrical erosion, and corrosion by lead-containing fuels—spark plug manufacturers make electrodes of a *Platinum* metal alloy.

This critical application dramatizes one vital fact: the dependability of Platinum. No metal but *Platinum* will do the job as well.

It could pay you to use a Platinum Metal

Your problem might be readily and economically solved with Platinum Metals—where high temperature corrosion and spark erosion are involved, such as in aircraft spark plugs . . . where reliable make-and-break electrical contact is indicated, such as in low noise high fidelity transmission . . . where wear-resisting, non-tarnishing surfaces are required, such as for printed electrical circuits . . . where a combination of severe corrosion and erosion must be met, as in the case of spinnerettes for rayon production . . . where peak catalytic efficiency is required, as in the refining of high octane gasoline . . . or where product purity must be retained despite high temperatures, as in the case of lens glasses . . . the Platinum Metals have proved to be the most economical for certain critical equipment.

Industry is going to higher temperatures and higher pressures.

broad application
of thermionic converters
as power supplies
must await
a breakthrough in
high-temperature technology

thermionic

by **Dr. John A. Welsh,** *president,*
Flow Laboratories Inc.,
and the late **Dr. Joseph Kaye,** *president,*
Joseph Kaye & Co. Inc.

HIGH VACUUM *thermionic converter, developed by General Electric, produces electricity when the flame of a blowtorch is played upon it.*

NEARLY $10-MILLION will be spent on research and development in thermionics during the next 12 months, half by government agencies and half by industry. Without a doubt, thermionics is a major contender in the search for practical and economical production of electricity without moving parts.

Static power generation can be achieved by several means — thermionics, thermoelectricity, magnetohydrodynamics (MHD), and fuel cells. Both thermionics and thermoelectricity produce electricity by using the phenomena that every material surface emits charged particles, including electrons, in proportion to the material's temperature. In thermionic devices, however, electrons are emitted into a vacuum rather than a solid, thus requiring higher operating temperatures.

Surge toward application

Little more than laboratory curiosities seven years ago, thermionic generators have progressed to an advanced stage in 1961, complete with intense competition among manufacturers. Both General Electric Co., Schenectady, N.Y., and Thermo Electron Engineering Corp., Waltham, Mass., already list thermionic generators in their catalogs. Although these devices are not considered commercial items for broad application, they are suitable for incorporation into new design concepts.

The first application of thermionic generators most likely will be military, with nuclear radiation as a heat source, or in space power systems using radiation from the sun. These limitations are imposed by the very high temperature heat source required by the generators. Only a few costly high-temperature materials are available for construction, restricting applications to those where cost is not the first consideration.

Eventually, thermionic generators will be used wherever lightness in weight, silent operation, compactness, and unattended operation are important. Thus they will power beacons or information-gathering equipment in remote areas and provide future soldiers with a light, portable power plant to be carried as back-packs.

In addition, thermionic generators one day may strip all excess equipment from power generation plants, leaving just the generators. In today's power plant, coal or nuclear fuel produces heat to boil water to produce steam to drive turbines to turn the generators to produce electricity. As a result, the generator is but one component in a forest of boilers, pumps, heaters, preheaters, condensors, and turbines. The thermionic generator, when perfected, could do the job alone.

Edison's effect

Thermionics is based upon principles that have been known for many years. Among the 1,033 patents issued to Thomas Alva Edison, one dated 1883 describes the operation of a thermionic generator. In fact, the phenomena of generating electricity by thermionic means is termed the "Edison Effect."

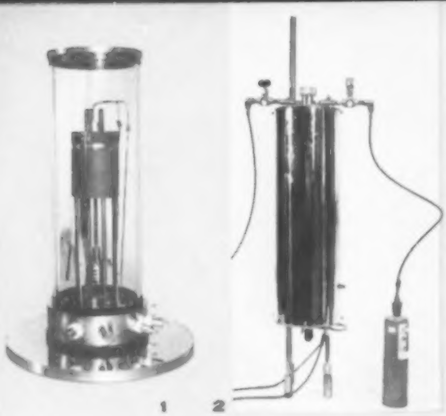
By 1923 all the physical understanding required for construction of vacuum-type thermionic generators had been achieved by Dr. I. Langmuir, General Electric Research Laboratory. Within the next 10 years, he completed almost all the basic work required for construction of cesium-type thermionic converters.

It was not until 1956, however, that anyone seriously proposed the thermionic generator as a practical source of electrical power. Dr. George N. Hatsopoulos described two types of thermionic converters in his doctoral thesis at MIT in 1956, and supported his conviction of their practicality by forming Thermo Electron Engineering Corp. to carry out the development and marketing of these generators.

Pros and cons of practicality

A profound, complete, and accurate study of vacuum thermionic generators was published by the English scientist Dr. Hilary Moss in 1957. His predictions on the performance of thermionic generators have been verified repeatedly by experiment. But he concluded that the generator was impractical and should not be considered further because of engineering difficulties in constructing the close-spaced cathodes essential to high efficiency.

Moss' conclusion was refuted the following year when several significant reports on experimental data were published. Dr. Karl G. Hernqvist, RCA Sarnoff Laboratories, Princeton, N.J. reported experimental power of 2.5 watts at an efficiency of 10.4%. Dr. Robert W. Pidd and his associates at Los Alamos Scientific Laboratory of the University of California reported open-circuit voltage of 4.5 volts and short circuit current density of 62 amps per sq cm from a generator



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using a nuclear reactor for a heat source.

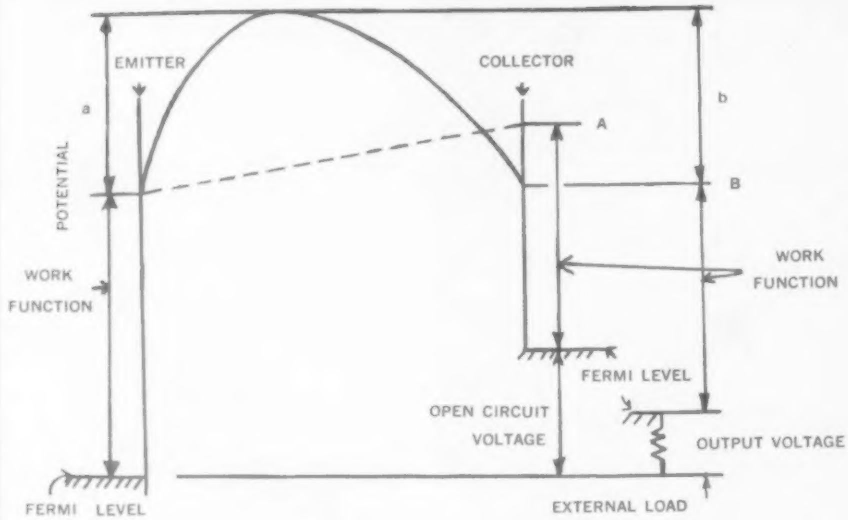
Dr. Hatsopoulos and Dr. Joseph Kaye published experimental data confirming Moss' analysis, but refuting his conclusion. A simplified analysis to aid the design engineer in producing thermionic generators was published by MIT professor Dr. Wayne B. Nottingham. And in 1959, four important papers were published by Dr. V. C. Wilson, Dr. H. F. Webster, and Dr. A. R. Houston, all of GE, and Dr. H. W. Lewis and Dr. J. R. Reitz, of Los Alamos Scientific Laboratory. Dr. N. S. Rasor, director of energy conversion at Atomics International, also began publishing significant articles in 1960. Now, the number of researchers in thermionics is increasing so rapidly that no list of authors can remain inclusive for more than two or three months.

The number of companies doing thermionic research also are increasing. Engaged in the field for the longest time and reporting the most significant work are Thermo Electron Engineering Corp., Radio Corporation of America, General Electric, and Atomics International. Aircraft and missile manufacturers now investigating thermionics are Martin, Boeing, United Aircraft, Lockheed, Thompson Ramo Wooldridge, General Motors, and Marquardt.

This concentrated research effort has resulted in many kinds of thermionic generators, such as the close-spaced vacuum diode, cesium thermionic diode, plasma diode, plasma thermocouple, and magnetic triode.

Principle of operation: hot to cold

Every thermionic generator contains a high temperature electron-emitting surface (cathode) and a lower temperature electron-collecting surface (anode). The number of electrons leaving the high-temperature emitter is much larger than the number leaving the lower temperature collector so that a net accumu-



DISTRIBUTION OF POTENTIAL *in a thermionic tube is shown above. The energy of electrons within the emitter is represented by their Fermi level.*

To leave the surface of the emitter, electrons must do a certain amount of work (emitter work function). Electrons migrate to the collector and build up a sufficient negative charge to prevent further electron migration between the electrodes.

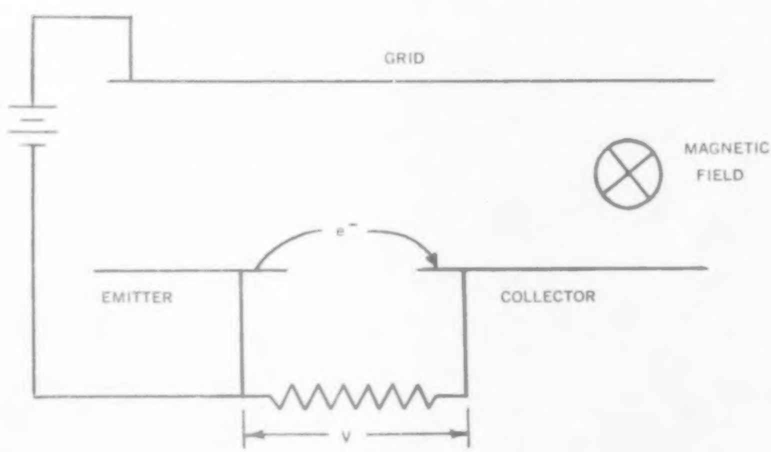
Point A is the potential at the collector. When this equilibrium has been reached, potential distribution between the plates is represented by a straight dotted line. Electrons entering the collector must give up an amount of work equal to the collector work function.

The electric potential difference between the electrodes is the difference in Fermi level (open-circuit voltage). The potential difference between Fermi levels is decreased to the output voltage when an electrical load is connected between the electrodes.

The collector work function remains the same and the potential at the surface of the collector, when current is flowing, is represented by point B. Because the charges moving from emitter to collector exert a retarding force on the electrons emerging from the emitter, potential distribution is altered and takes the form shown by the curved solid line.

Any electron leaving the surface of the emitter must climb a potential hill (a) before it can reach the collector and contribute to an electric current in the external load.

To reach the collector, the electron must climb a hill at least up to point B; any additional hill (b) is an undesirable barrier to the flow of current, called the space charge barrier.



MAGNETIC TRIODE *diagram shows the two plates of a diode placed in the same plane with a grid a short distance above in a parallel plane. A magnetic field deflects electrons from the emitter to the collector.*

3

RECENT THERMIONIC *developments include: (1) Thermo Electron's 200-watt thermionic generator; (2) Atomic International's flame-heated generator; (3) RCA's diode for materials investigation (above) and experimental plasma triode energy converter (below); and (4) steel ball and dry ice illustrating spacing regulations in ITT's study of close-spaced diodes.*

4

lation of charge builds up on the collector. Thus, a sufficient potential difference is created between the two surfaces to drive electric current through an external load connected between the two electrodes.

A fuller understanding of the thermionic generator may be had by examining the diagram at top of page 52. It is evident that any electron arriving at the surface of the collector has sufficient energy to do work equal to the sum of the collector work function and the output voltage.

The electron is not concerned at all with how these two quantities vary, as long as the sum remains the same. Since output voltage represents the useful electrical work and collector work function represents heat dissipated in the collector, it would be desirable to reduce the size of this work function to a minimum.

In thermionic generators, the value of the collector work function is about 1.85 volts, while the output voltage is about 0.5 volts. If the work function could be reduced by 0.1 volts, the output voltage (or power) would increase by 20% to 0.6 volts. If the collector work function were reduced by 0.5 volts, the output power would double to 1.0 volt.

Considerable research effort is being placed on the materials problem, and some success has been reported. A stable collector work function of 1.65 volts has been reported by Hatsopoulos and a work function as low as 1 volt was reported at GE by Dr. L. R. Koller, now with National Research Corp., Cambridge, Mass. However, these low work function surfaces have yet to be engineered into a thermionic generator.

Another point evident in the diagram is the desirability of reducing the space charge barrier, b, to zero. In fact, reduction of the space charge barrier is crucial to the success of thermionic generators.

Several methods have evolved for reducing the barrier. For instance, the number of electrons moving between the plates can be reduced by decreasing the spacing between the plates. To achieve efficiencies of greater than 10% with reasonable power densities, spacing must be about 0.0004 in. Thermionic generators of this type are called close-spaced vacuum diodes.

Agile electrons pose a problem

A grid with a small positive potential placed between the plates also may be used to reduce the space charge barrier. This method is sound except for one fact: electrons are superbly agile. No matter how fine the grid structure, electrons find it and enter it rather than proceed to the collector. Therefore, power consumed by the grid is greater than power produced by the thermionic generator.

The most successful scheme for reducing space charge barriers is a variation on grid structure. Positive ions injected between the plates tend to cancel the negative potential created by electrons. Again, electrons can find these positive grids; however, the size of the ion compared to the size of the finest grid structure is like that of a green pea compared to a barn door.

All thermionic generators that use this method of space charge reduction utilize the positive ion of cesium. Cesium is used because its ionization potential is lower than the work function of available high-temperature emitters. Ionization potential represents the work necessary to remove an electron from an atom. Work function represents the work necessary to remove an electron from a surface. In a sense, these two physical properties represent the electron for the atom or for the surface.

When a cesium atom comes in contact with a surface such as tungsten at high temperature, the cesium atom is boiled away from the surface, but the other electron of the cesium atom finds itself more strongly attracted to the tungsten surface than to the cesium atom. Therefore, the electron remains with the tungsten and allows the cesium to depart as a positive ion.

Cesium boosts work function

Cesium offers other advantages. An even coating of cesium deposited on the surface of an emitter will give it the work function of cesium metal, 1.87 volts. A cesium coating can be obtained by maintaining the temperature of the surface at a sufficiently low value. This means that the collector work function can be maintained at 1.87 volts regardless of the material used for electrode structure.

Emitter work function must be maintained at a high enough value to generate positive cesium ions. However, the amount of current emitted is decreased greatly by the high work function. To generate a copious supply of electrons, there must be low work function regions on the emitter surface. These regions can be achieved by depositing a partial layer of cesium metal on the emitter surface. The cesium-coated portion emits electrons and the bare metal emits positive ions.

Emitter temperature and pressure of the cesium vapor in contact with the surface determine the fraction of the emitter area covered by cesium metal. Emitter temperature is controlled by the heat source and heat-transfer method. Cesium pressure is maintained by controlling the temperature of a liquid pool of cesium. Cesium vapor pressure, in equilibrium with the liquid pool, is determined by the liquid temperature. Temperature of the collector is controlled by the heat transfer from that electrode.

Thus, by controlling three independent temperatures, it is possible to control emitter and collector work functions, number of electrons emitted, and number of positive ions generated. By proper selection of these temperatures, a balance can be achieved between the electron and positive ion emission to eliminate the space charge barrier.

For small current density, spac-

Dr. John A. Welsh (left) and the late Dr. Joseph Kaye are among the foremost authorities on thermionics research. As president of Flow Laboratories, Welsh now is pioneering research and development of a biochemical fuel cell. He formerly was on the staff of Joseph Kaye & Co., Thermo Electron Engineering Corp., and MIT. With Kaye, former MIT professor, Welsh co-edited the book "Direct Conversion of Heat to Electricity." Their article in this issue was completed four days prior to Dr. Kaye's death. Dr. Kaye also had authored 60 papers and two other books.

ing between the emitter and collector is relatively unimportant. Plates separated by about 0.004 in. may have no space charge barrier. As current density is increased, the number of positive ions also must be increased and the probability for collision between these particles becomes significant. It is necessary then to reduce spacing between plates to less than the mean-free path of the electron.

The mean-free path increases with temperature, so that reasonably large spacing may be used if the emitter is operated at a sufficiently high temperature. For practical temperature, however, it is necessary to reduce spacing to the magnitude required for close-spaced vacuum diodes. For instance, at an emitter temperature of 4040 F, spacing can be about 0.002 in. At 3140 F, spacing should be about 0.0004 in.

Cesium modes of operation

Cesium generators are identified by several names, including cesium thermionic diode, plasma diode, and plasma thermocouple, the names describing various modes of operation of the cesium diode.

When a sufficient number of positive ions is generated to neutralize the negative space charge, the generator is a cesium thermionic diode. If an excess of positive ions is generated, a positive space charge forms at the electrodes and the region between the plates becomes a plasma or neutral gas composed of positively and negatively charged particles. This mode of operation is referred to as a plasma diode.

Pressure of the gas between the electrodes is quite low in these two diodes; therefore, the number of particles in the space is small enough to be treated by kinetic theory and the mechanics of individual particles. When pressure is increased and this theoretical description begins to lose its validity, as in the case of high cesium pressure with large spacing, operation of the diode may be described by the thermodynamics of irreversible processes. Thermionic generators then take on the characteristics of thermocouples and such diodes are called plasma thermocouples.

The magnetic triode

Another method for reducing the effects of the space charge barrier is the magnetic triode. It is not as well developed as the diode, but is gaining increased interest. A grid placed between the electrodes tends to intercept a large fraction of current passing through. If electrons can be forced to travel in selected paths that do not intercept the grid, this method might have merit, since larger spacing between the electrode would result. This task can be accomplished by using controlled electric and magnetic fields.

The diagram at bottom of page 52 shows the two plates of a diode placed side by side in the same plane. A grid is placed a short distance above the electrodes and in a parallel plane. Because of the positive potential on the grid, electrons emitted from the hot emitter are accelerated toward the grid. A magnetic field perpendicular to the line joining the centers of the plates is imposed. This field deflects the electrons into a cycloidal path that leads them from the emitter to the collector.

Since no current reaches the grid, no power is consumed by the grid. Because the magnetic field always acts perpendicularly to the direction of travel of the electrons, no power is consumed from the field. The potential on the grid may be adjusted to control the space charge barrier at the surface of the emitter, and the magnetic field may be varied to insure that the electrons follow the desired path. This device has been termed a magnetic triode.

In all diodes, heat flows directly from the emitter to the collector by radiation. In the triode, heat flows from the emitter to the grid and then from the grid to the collector. Heat flux is reduced just as though a radiation shield had been placed between the plates of the diode. Thus, minimum heat loss can be cut in half and efficiency doubled.

Directions of the future

The greatest need in thermionics is materials. Cathodes evaporate in the high vacuum required for thermionic emission; cesium corrodes the vacuum seals, and heat leaks through the structure. As much effort is being expended on materials research as it is on understanding the thermionic phenomena; thus significant developments ought to come in the high temperature technology associated with thermionics.

Although basic understanding of thermionic converters is reasonably well advanced, two areas remain to be examined in depth. First is the heat transfer in practical devices. Inherent in the heat transfer problem is the mechanical design problem of fabricating a satisfactory structure to withstand the combined stress due to inertial and thermal loads.

Much engineering must be done to capitalize on methods of improving the heat transfer coefficient between heat source and emitter. The mechanism of heat transfer may be improved by utilizing catalytic reactions occurring on the back surface of the emitter or on surfaces in direct contact with this hot electrode.

A second area for examination is the heat source itself. Since thermionic generators operate at temperatures near the melting point of steel and higher, it is almost impossible to build a conventional heat source such as gasoline and air. Regenerative heating of incoming air may overcome the problem, but there are limits to the amount of preheating possible. A satisfactory heat source could be constructed by using acetylene as the fuel, or replacing air by oxygen.

Many of the problems remaining to be solved are in the area of basic physics having to do with understanding principles of operation of thermionic devices. But in the authors' opinion, high-temperature materials technology, heat-transfer techniques, and development of a satisfactory heat source are more important in the immediate future.

As long as thermionic diodes remain high-temperature devices, they will be used more as topping generators than as primary sources of electricity. A new development by Dr. Hernqvist at RCA has produced a thermionic converter operating at about 2000 F. Should this development be broadly applicable, it could put thermionic converters in the class of fuel cells, most promising of all devices for power supply. ■

magnetohydrodynamic
generators
do not fit into
conventional
energy conversion schemes,
such as
fuel cells, that
convert chemical energy
into electricity . . .
nor are they like
thermionic devices that
convert heat directly
into electricity . . .
magnetohydrodynamics
for power generation
basically consists of the
direct conversion of
the energy content of hot,
high-speed
gas flows into
electrical energy

mhd

MAGNETOHYDRODYNAMIC GENERATORS may substantially increase the conversion efficiency of heat to electrical power. However, industrial application of this concept still requires a solution to conductivity and materials problems. The successful design of a practical MHD generator with an a-c output also is needed to reduce the cost of capital equipment and hasten its adoption by industry.

MHD generators are distinguished from other conversion devices by the fact that maximum efficiency of conversion is not limited by thermodynamic considerations, but by the finite conductivity of the gas.

Magnetohydrodynamic generation of power is not a new idea. It is based on British scientist Michael Faraday's important discovery that the relative motion of a conductor and a magnetic field induces an electromotive force in the conductor. Connecting a load across the terminals of a conductor causes an electric current to flow through the load. The concept of using a conductive fluid flowing in a static magnetic field constitutes the essential idea for MHD generation of electrical power.

Tidal power of the sea

As early as 1832, Faraday experimented with the flow of mercury in a magnetic field and the extraction of power from the tidal motion of sea water in the earth's magnetic field. Little by way of application came out of these early experiments, presumably due to early commercial success with rotating dynamos.

Starting about 1910, a number of patents have been granted by the U.S. Patent Office for methods to generate electrical power by the flow of fluids through applied magnetic fields. The advantage of thermal energy in a hot gas (which can be converted easily to the kinetic energy of the gas) as a source of electrical power production was recognized early by inventors. Thus, most of the patents granted after 1915 refer to the use of gases as the working fluid.

Despite the abundance of patents in the field, only recently have MHD power generation experiments been successful. Breakthroughs were announced almost simultaneously by the Space Sciences Laboratory of General Electric Co., Philadelphia; Avco-Everett Research Laboratory, Everett, Mass.; and Westinghouse Research Laboratories, Pittsburgh. Current efforts undoubtedly were spurred by the advent of the space age.

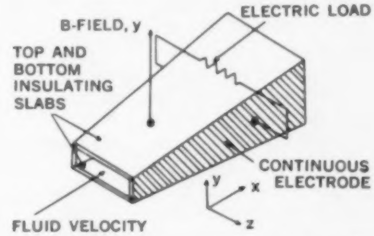
Efficiency at high temperatures

Gaseous magnetohydrodynamic generators have three main advantages over conventional turbogenerators — efficiency, versatility, and simplicity.

- *Efficiency*, the main attraction in MHD power generation, results from fuller utilization of high temperatures attainable in the combustion process. Conceptually, in a combined magnetohydrodynamic and turbine cycle, combustion gases (properly mixed with easily ionizable materials) enter the magnetohydrodynamic generator, where power is extracted from the gas and its enthalpy (heat capacity plus kinetic energy) is reduced. Then the gas preheats the combustion mixture, which brings down the gas to a temperature suitable for conventional boiler operation. Thus a higher overall efficiency is obtained.
- *Versatility* of MHD generators, from a systems point of view, is claimed because both stationary and auxiliary power applications are possible. This is true especially when a high-temperature gas is readily available, as in a rocket exhaust or the flow field surrounding a hypersonic vehicle in the atmosphere.
- *Simplicity* results from the absence of rotating machinery in MHD generators, and easier maintenance and flexibility in design and operation are possible.

The heart of MHD generators

The magnetohydrodynamic channel through which the conducting gas flows is the heart of the MHD generator. The straight channel below can be designed to keep any

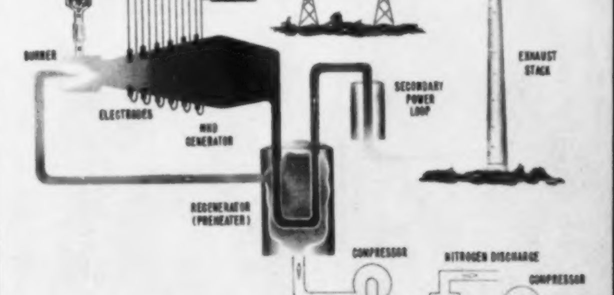


one of the various thermodynamic quantities (entropy, temperature, pressures, velocity, etc.) constant throughout the length of the channel. The straight channel thus has a decided advantage of superior operational flexibility.

Spiral and coaxial channels are advantageous in that the length of interaction of the ionized gas flow with the magnetic field can be increased with only a small increase

by **Dr. Mahendra Singh Sodha,**
senior physicist, Armour Research Foundation

MHD COMMERCIAL POWER *generation cycle using oxygen-enriched air (right) is being studied by Avco Corp. and 12 power companies. The cycle begins at the air inlet (lower right of chart) and is completed when the gas passes through a secondary power loop to the exhaust stack. Oxygen-enriched air instead of air itself permits the use of conventional materials for pre-heater construction. Experiments using combustible fuels are conducted on the MHD generator constructed by Westinghouse scientists (left). The device produces electric power equivalent to approximately one watt.*



in generator weight. Hence, they are of special significance in flight and space vehicles where generator weight is of prime consideration.

Scientists at the Tapco Group, Thompson Ramo Wooldridge Inc., Cleveland, have devised a scheme in which gas particles travel spiral paths in the magnetic field so that gas flow is a vortex motion. They claim a very low power-to-weight ratio for their generator shown below.

Open and closed cycles

Estimates of the performance of coal-fired open cycles and nuclear-fueled closed cycles have been made by Dr. Arthur Kantrowitz, director of the Avco-Everett Research Laboratory and Philip Sporn, president of American Electric Power Service Corp., New York, and Dr. L. Steg and Dr. G. W. Sutton, at the GE Space Sciences Laboratory. Although these estimates were made in the absence of reliable data, they are indicative of the advantages of a combined magnetohydrodynamic turbine cycle over the conventional turbine cycle.

In the cycle considered by Steg and Sutton and their collaborators at General Electric, the flame gases leave the combustion chamber at a pressure of 5.5 atmospheres and a temperature of 4730 F. After mixing with easily ionizable chemicals, they enter the nozzle and the generator.

With more than three-million pounds of gases per hour passing through the generator, output power is 300 megawatts, of which about six go to provide the magnetic field, 15 are lost in its conversion to a-c, and the remaining 279 megawatts are available as usable a-c power. The hot gases leave the diffuser at the generator exit at a pressure of 1.4 atmospheres and temperature of 4100 F, preheat the air going into the MHD generator, and pass through the boilers to escape in the atmosphere.

Steam leaves the boiler at 1000 F and 2400 psi, goes through the high-pressure turbine which drives the air compressor, and returns to the boiler for reheating to 1000 F. After reheating, the steam enters the reheat turbine at 488 psi to produce 91 megawatts of a-c power and then passes on to the low-pressure turbine where it produces another 173 megawatts of power before being condensed.

After also allowing for other losses, such as ohmic heating, eddy current, and end loss, net station output is 523 megawatts at a heat rate of 6687 Btu per kilowatt hour, corresponding to a *thermal efficiency of 51%, which is about 20% higher than that of the best steam cycles currently in operation.*

The coal-fired open cycle discussed by Kantrowitz and Sporn is similar to the one described above and leads to an estimated thermal efficiency of 55%.

Dr. Stewart Way, of Westinghouse Research Laboratories, has predicted thermal efficiencies as high as 60% with a proposed closed cycle system using helium gas seeded with 1% cesium. However, reactors operating at about 4000 F, as proposed by Way, have not yet been built.

A few novel concepts, like the dust fuel reactor conceived by Armour Research Foundation, Chicago, look very promising as a source of high-temperature gases. Armour scientists visualize MHD generators as components of the reactor loop. Nuclear fuel would be suspended in a gaseous coolant, such as helium, with the suspended fuel circulating in a closed loop.

An advantage of the closed cycle is that you are not limited in the choice of working gas and seeding agent because the same gas can be used repeatedly in the cycle.

Two points should be clearly stated here. First, the efficiency estimates above should not be taken too seriously at this stage, since they are based on educated guess rather than experience. Second, MHD generators do not require high temperatures because of thermodynamic restraints, but rather because high temperatures are necessary to obtain the high conductivity of gases required in the generator.

Toward an a-c generator

A drawback of magnetohydrodynamic power generation is the d-c character of the output. At present, the cost of equipment to convert d-c to a-c is a large part of total capital costs. Thus, the attractiveness of a magnetohydrodynamic generator would be increased greatly if a practical generator yielding an a-c output were available.

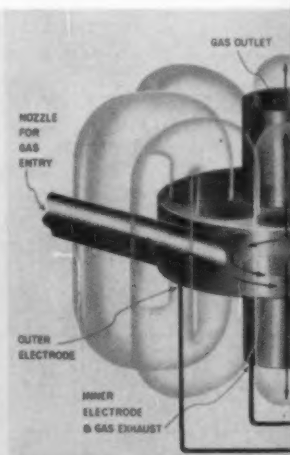
The obvious method of using an alternating magnetic field is not acceptable because of the large loss of energy of the magnetic field in the gas as well as the magnetic materials. L. P. Harris, of GE Research Laboratories, Schenectady, has proposed a generator channel with a three-phase winding similar to those used in linear induction pumps for liquid metals.

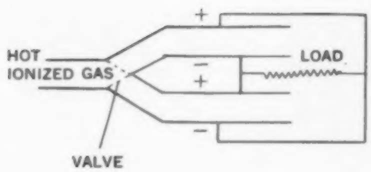
Analyses of channel flows have shown that such a device can operate with high efficiency at a high power if the conductivity of the gas is very much higher than that necessary for a d-c generator. Higher conductivity requires much higher temperatures, and for this reason the Harris concept today is only of academic interest.

Another idea for a possible a-c generator has been proposed by Armour Research. Two or more flow

*Magneto-hydro-dynamics is the science of the interaction of moving and conducting fluids with magnetic fields. Synonymous with magnetohydrodynamics are magnetofluiddynamics, magnetofluidmechanics, magnetogasdynamics, hydromagnetics, and MHD.

HOT HIGH-SPEED GAS *spirals through magnetic field in vortex MHD power generator (right) developed by Thompson Ramo Wooldridge. Allis-Chalmers' small pilot generating unit (left) is used to demonstrate the effect of flux density, gas velocity, gas temperature, and increased output realized by seeding the flame with an electrolyte metal.*





channels and a valve, connected as shown above, would conduct the gas flow alternately through the two channels. The magnetic field is perpendicular to the plane of the drawing, causing an alternating current to flow through the load.

Thus, the desired shape of the output—a sinusoid (see definition on page 49)—can be achieved by a proper design of valve and other parameters. In its simplest form, the valve may consist of a disc with one or more holes rotating in front of the channel openings. The valve also may use gas jets to alternate the flow.

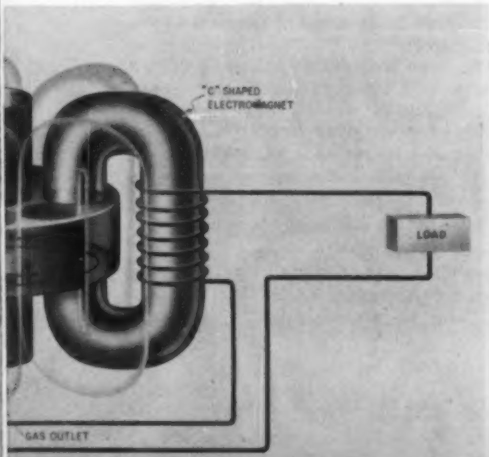
Limitation of materials

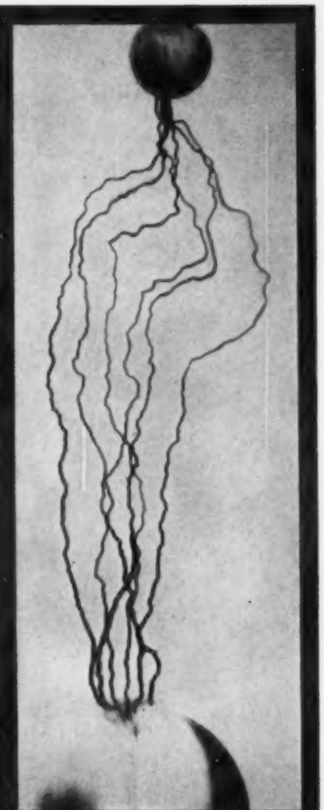
In a suitable MHD power generator system, the material of the channel walls must withstand the effect of corrosive hot gases at high pressure and temperature flowing at high velocities for considerable periods—for months in a stationary power plant.

Properties of materials that may be considered for channel wall construction materials have been tabulated by Steg and Sutton. These materials include the oxides of silicon, aluminum, zirconium, thorium, and hafnium; calcium, strontium, and barium zirconium trioxides; zirconium, tantalum, and hafnium carbides; and graphite, pyrolytic graphite, and boron nitride.

With the exception of silicon, aluminum, zirconium, boron nitride, and graphite, all are relatively new and exotic so far as applications are concerned. Research on high-temperature properties and fabrication techniques of these materials should be pursued vigorously.

Cathode material also is a problem in MHD power generation be-





cause of the difference in the mechanism of current extraction from a metallic conductor and a gaseous conductor. In a gaseous conductor, electrons are thermionically emitted by the cathode and, because of the potential difference, are accelerated toward and absorbed by the anode. Hence, one limitation on the available current is set by the thermionic emissive properties of the material.

Graphite and thorium are expected to be satisfactory materials for temperatures of about 3000 K. However, to get gases of suitable conductivity at lower temperatures, say 2500 K, unconventional means of electron emission must be found for making maximum use of the generator. Photoelectric emission is an interesting possibility.

The future of magnetohydrodynamic power generation depends largely on whether conductivity of readily available gases can be made high enough—about 100 mhos (reciprocal ohms) per meter—at reasonable temperatures (2500 K) for efficient operation of the generator. For an understanding of this problem and its implications, an elementary knowledge of the theory of electrical conduction in gases is necessary.

Electrical conduction in gases

In a gas at any temperature, some of the molecules are ionized, or broken up into electrons and ions (positively charged particles of about the same mass as the molecules).

Most of the current in a gas results from the motion of electrons, while a much smaller portion is contributed by the motion of ions which in almost all cases can be neglected.

The conductivity of a gas increases with the increasing number of electrons per unit volume and decreases with an increase in the collision frequency of electrons.

The number of electrons in a gas can be increased by adding easily ionizable gases or the solid-particle dust of a material that is a good emitter of electrons. But these methods also introduce into the gas additional particles that scatter electrons and thereby raise the collision frequency. Hence, conductivity attains its maximum value at an optimum concentration of these additives.

If we use more additives than the optimum concentration, conductivity rapidly decreases because of the resulting increase in collision frequency. However, the necessary data for calculation of the optimum concentration, for most cases of practical interest, is either not available or unreliable.

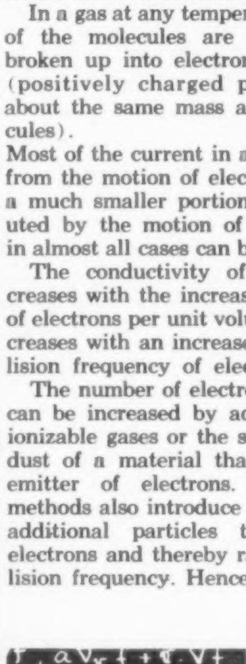
In the presence of a magnetic field, conductivity becomes a tensor, the components of which can be expressed analytically. The conditions for optimization of conductivity in the presence and absence of magnetic field are different. A detailed kinetic theory of the interaction of electric and magnetic fields with an ionized gas flow is not available. This fact presents a serious handicap for those who try to optimize performance of a magnetohydrodynamic generator.

Seeding gases

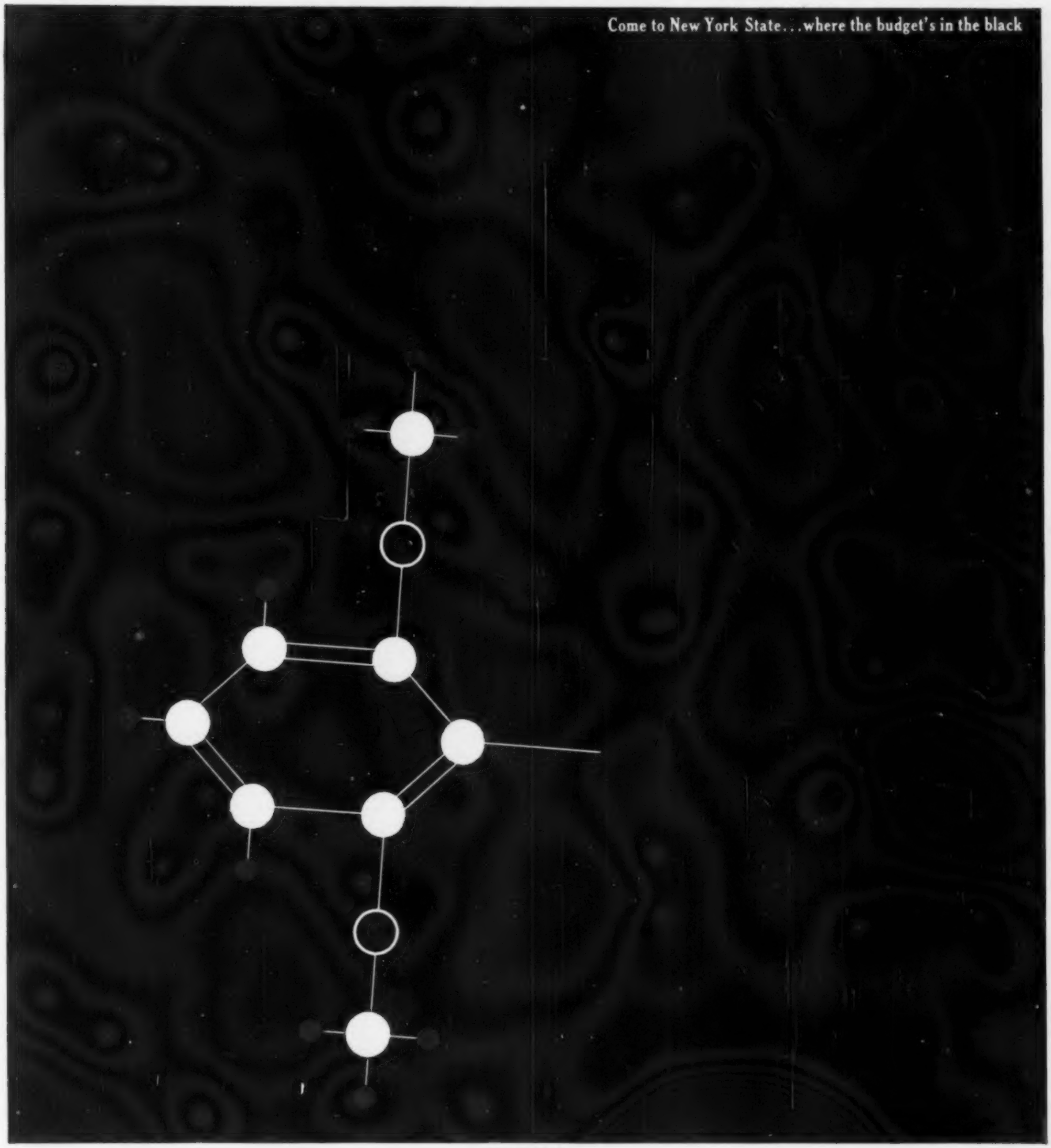
Most experiments on the electrical properties of hot gases were made with easily obtainable gases. Recently, however, a number of interesting measurements have been made on seeded combustion products of a propane oxygen mixture at GE Research Labs.; the JP-4 oxygen mixture at Avco-Everett; and oxygen diesel oil, butyl cellosolve, and a potassium 2-ethylo hexoate mixture at Westinghouse Research Laboratories. Conductivities from one to 100 mhos per meter have been reported under various conditions.

The current trend of research in magnetohydrodynamic power generation is toward hardware. MHD generators with large capacities are being planned and built. Compact generators for space applications also are under development.

Yet, the development of an economic and efficient MHD generator is to a large degree dependent on breakthroughs in materials, gas conductivity, or a practical design of a generator with an a-c output. A maximum return in hardware can come only from effort invested now in these basic areas of non-hardware research. ■



A theoretical physicist at Armour Research, Dr. Mahendra Sodha is a specialist in the physics of ionized gases. He has published numerous papers on this subject and on semiconductors, optics, combustion, and ballistics. A fellow of the American Physical Society, he was chairman of the magnetohydrodynamics session of the 1960 National Electronics Conference. Dr. Sodha received his PhD from the University of Allahabad.



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N.Y.S.

solar machines in space

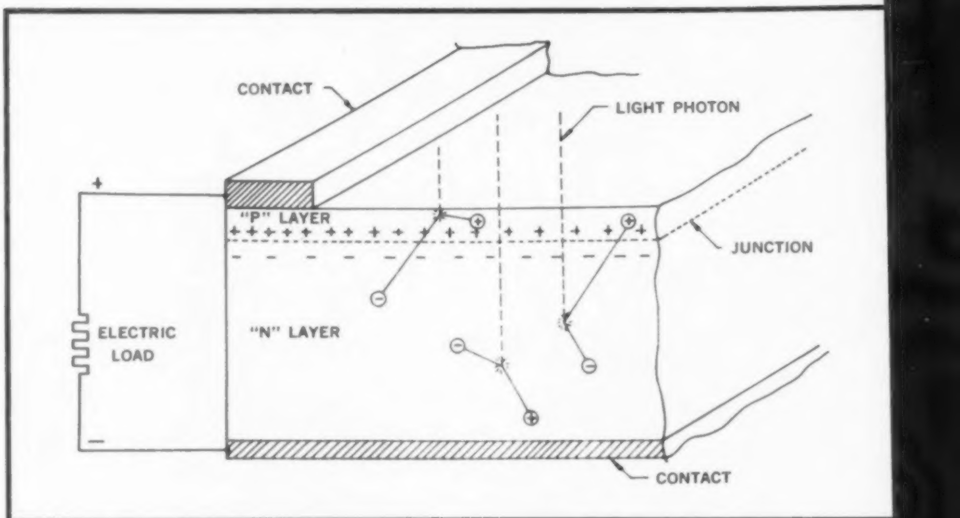
DIRECT CONVERSION OF SUNSHINE to electric power has not been particularly practical on the earth because alternate power sources are far cheaper. But directly converted solar power is the only practical source of energy for long-flight space vehicles. • The usefulness of sunshine as a spacecraft energy source has resulted in tremendous development effort being applied to machines for converting sunshine into electric power. Techniques actually have advanced as much in the last five years as in the preceding 100 years, the most significant developments being silicon solar cells, solar concentrators, thermionic converters, Stirling-cycle engines, and mercury turbines. Silicon solar cells normally are exposed to unconcentrated sunshine; other converters require concentrators to produce high temperatures. • Announcements and technical papers following the invention of the silicon solar cell in 1954 at Bell Laboratories discussed applications such as powering remote telephone stations, providing emergency power in life boats, charging flashlight batteries, and eventually supplying the energy needs of mankind. But scarcely a word was said about the use of solar cells for space vehicle power supplies then or until 1957! ◁ *A new type solar cell shown at left, 10 to 100 times more resistant to damage from radiation in space, has been developed by Signal Corps scientists and is undergoing radiation tests at RCA Laboratories* • Solar cells today are comparatively efficient, up from 6% to 15% in the laboratory. (You can *buy* 13% efficient solar cells.) High-efficiency low-cost cells

by **Henry Oman,** *research specialist, Aero-Space Div., The Boeing Co.*

are still in the future, although low-efficiency (less than 4%) "cull" cells can be had for some 60 cents. While earth surface applications of solar cells have been insignificant to date, large factories are turning out solar cells for satellites and space probes.

Solar cells for space use normally are connected in series and parallel to form an array. Failure of one cell in a large array will result in only a fraction of a percent loss in array power output. Thus, extra capacity against micrometeorites and other hazards can be provided with little extra weight. Orientation need not be precise; misorientation of eight degrees will result in only a 1% loss in power output. These features are difficult to attain in other solar power supplies.

A typical solar cell is composed of a "slab" of high-purity silicon, 1 by 2 cm in area and 0.4 mm thick. During manufacture, single-crystal bars are slowly withdrawn from molten silicon. Later, the bars are sliced with diamond saws, and the slices shaped, polished, and doped with impurities. Contacts are added manually, and the cells are tested for performance.



Problems: weight and cost

The principal problems of solar-cell power supplies — weight and cost — are compounded by the fact that the high conversion efficiencies quoted by manufacturers are not attainable in space sunshine. One reason is that solar-cell performance normally is measured at 82 F, whereas in space the cell will operate at a temperature of 104 F. Every 36 F rise in temperature causes a 1% drop in efficiency.

Another reason is that efficiency-measuring techniques have not been realistic. Originally, performance of a reference solar cell was measured outdoors in sunshine. Then an ordinary tungsten lamp was placed relative to a test area so that the reference cell produced the same output as it did in outdoor sunshine. Performance of subsequent "improved" cells was measured under the same lamp. However, the spectrum of the lamp contained more red and infrared light than did sunlight in space, and any cell that had good sensitivity in the red and infrared region of the spectrum showed good performance when tested under the lamp.

Recently some of these "improved" cells were tested on a mountain top where the solar intensity and spectrum approached space conditions. It then was discovered that the new cells did not produce the expected output in sunshine.

Within the last year, manufacturers have found ways of improving the sunlight-performance of cells. Sensitivity of a solar cell to the violet part of the sun's spectrum has been improved by making the p (positive)-layer of the cell thinner. This permits violet light to penetrate farther toward the junction. A conducting grid on the surface of the cell compensates for the reduced conductivity of the thinner p-layer.

Concentrating sunlight on solar cells is a method of boosting their power. Doubling power output per cell halves cell cost, and if lightweight reflecting surfaces could be substituted for silicon photovoltaic material, the weight per kilowatt also might be reduced. Weight could be reduced even more significantly if the reflecting material also could support the structure.

Light intensities beyond four or five times that found on earth during a bright day are not practical for solar cells, because great intensities produce high cell temperatures that reduce efficiency. Furthermore, the output of a solar cell is not proportional to illumination intensity; rather it drops off at higher illuminations. Solar cells, therefore, should have low concentration ratios. (Concentration ratio is radiation intensity at the absorber, or solar cell divided by the radiation intensity of the ambient sunshine).

For low concentration ratios, the Somor concentrator, named after its inventor, appears advantageous because the absorber does not shade effective area of the concentrator, and the concentrator surfaces can radiate heat to keep the cells cool. One Somor concentrator designed specifically for solar cells is shown on page 65. High-altitude tests show that a Somor concentrator in space could increase solar cell power output by 80%.

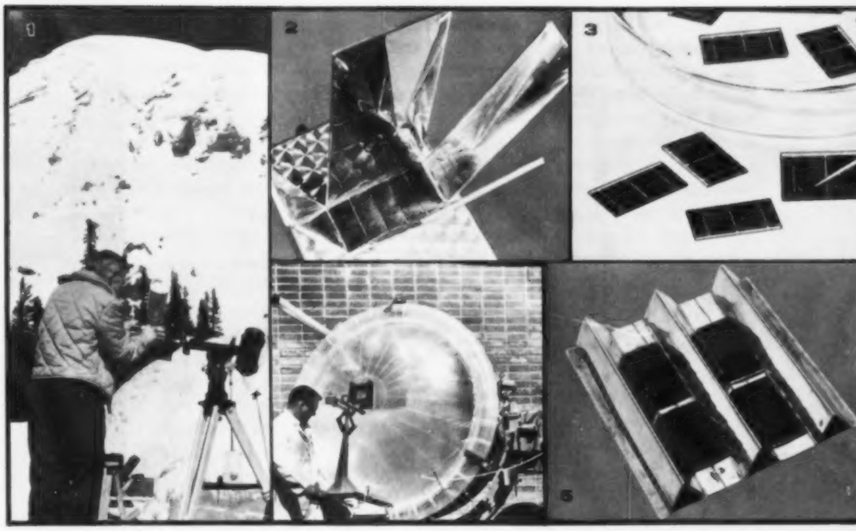
Early uses of sunpower

The history of direct sunpower utilization is long. Burning glasses were used in Nineveh for igniting altar fires, and Archimedes reportedly used a mirror to set fire to Roman warships within bow-shot. The first use of sunlight for running a heat engine came in 1870 when August Mouchot of France generated enough steam to run a small engine by concentrating solar rays on a glass boiler with a conical mirror. A large solar power plant was constructed on the banks of the Nile river in 1913 by Frank Shuman, of Philadelphia, and Prof. C. V. Boys, of England. It employed three trough-type reflectors 14 by 205 ft long to generate enough steam to produce 50 to 60 hp for driving irrigation pumps.

In all of these devices and in their modern counterparts, concentrated sunlight is necessary to operate high-temperature heat-to-electricity converters. Sunlight can be concentrated with lenses or mirrors. If made of glass, lenses are too heavy to be considered seriously for space use. Lightweight plastic lenses can be used to concentrate sunlight, but they are likely to be deteriorated by the ultraviolet radiation.

Many configurations of reflecting or mirror type concentrators are possible. The Somor, Archimedes, and Shuman concentrators are being developed for space use. The Somor

SILICON SOLAR CELL *operation is illustrated by diagram at left. When a hole-electron pair is created by absorption of photons, the electron returns through the external circuit where it constitutes a current flow.*



HIGH-ALTITUDE TESTS *on solar cells are conducted* (**1**) *at Boeing in a Somor concentrator.* (**2**) *A model shows Electro-Optical's lightweight solar collectors combined with solar cells.* (**3**) *International Rectifier's gridded silicon solar cells provide increased power.* (**4**) *Electro-Optical's inflatable solar concentrator is tested.* (**5**) *Boeing's solar cells are shown in a Somar collector.*

concentrator, as mentioned, works well for silicon solar cells where only a small concentration ratio is required. Archimedes and Shuman concentrators are being developed for high-temperature applications where solar heat is converted into electricity. With both of these concentrators, a circular configuration is usually employed; the Shuman concentrator would be a paraboloidal dish.

30 sq yds of mylar = 1 lb

Early space-vehicle concepts called for large inflatable paraboloidal solar concentrators made of aluminized mylar to provide heat to run the electric power generators. Thirty square yards of aluminized mylar 0.0005 in. thick weigh only a pound; with a reasonable assumed efficiency of 25% it was easy to conceive of power plants producing hundreds of kilowatts and weighing only 5 to 10 lbs per kilowatt.

Careful thought has brought some important realities to light, however. For example, one would seek high overall efficiency to reduce concentrator and radiator size. The efficiency of a heat-to-electricity converter is a function of source temperature, which must be high for good efficiency. And high temperature can be achieved only with a precise concentrator. For example, for the efficient achievement of a 2900 F absorber temperature, required to operate a thermionic converter, a concentrator is needed that has a circle of least confusion smaller than the sun's image. (The circle of least confusion is the disc-like spot formed at the focus of a concentrator from a point source of light.) This focal image would be a point if the concentrator were perfect.

The sun's image for a 2-ft focal length is only 0.15 in. in diameter. Orientation is so critical that a 15% drop in concentrator-absorber efficiency occurs if the concentrator is misoriented by a quarter degree of arc. Such accuracy cannot be attained with inflated structures.

In a space vehicle, the concentrator forms an image of the sun at the focus. The absorber must be large enough to cover the hottest part of this image, plus the area in which the image wanders as a result of orientation errors. The concentrator must be designed to fit the mission of the vehicle. In space near the earth, for example, radiation intensity is about 130 watts per sq ft, but at Jupiter it is only 5 watts per sq ft. This means that for a given amount of power, a concentrator for use at Jupiter must be 26 times as large as a concentrator for service near earth.

The imperfect absorber

The absorber converts radiation to usable heat at the focus, but it is not perfect and will reflect some radiation. This reflection loss can be reduced by making the absorber black. However, because of its high emissivity, a black absorber is a good radiator of heat, and thus causes a re-radiation loss. Much has been done to make selective absorbers appear black to solar radiation and yet have low emissivity (appear shiny) to infrared wavelengths, thereby forming a heat trap. Some of these surfaces are so effective that if one is used to cover a teakettle and placed in unconcentrated sunshine, the water inside will boil.

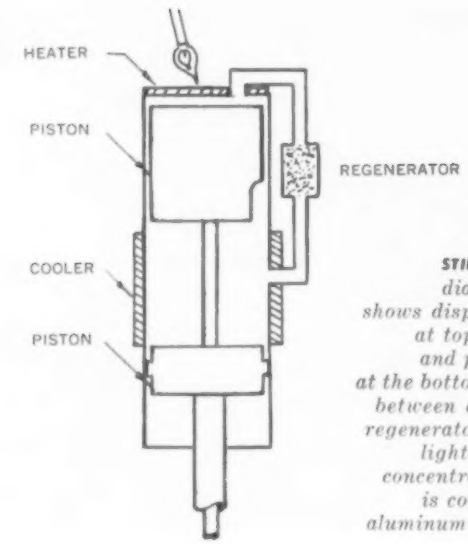
Presently available selectively absorptive surfaces are limited to about 950 F. For higher absorber temperatures, for example 2900 F, a cavity absorber often is used. This design permits a large absorber area behind the cavity aperture; yet re-radiation occurs only from the aperture area. The catch is that the concentrator must be precise enough to focus sunlight through the small aperture without appreciable spillage on the aperture plate.

Construction of concentrators

Several approaches are being taken in the construction of concentrators for space use. One is to apply a reflecting surface on a thin substrate, such as mylar, and support the assembly in space by rigidizing plastic foam. The reflecting surface and its substrate are folded into a small volume during vehicle launch and erected mechanically after the vehicle is in space. A problem is distortion of the face caused by flow of the viscous foam mixture before and during extension.

Another approach is the Fresnel concentrator, a variation of Archimedes' mirror array. The reflecting face in the Fresnel concentrator is composed of a number of circular elements that reflect sunlight toward the absorber. Because of its flatness, this concentrator can be stored and erected in a variety of ways.

One method of manufacturing a Fresnel concentrator is to make a very precise master and electroform a metallic replica on the master. The electroformed surface



Stirling engine diagram (left) shows displacer piston at top of cylinder and power piston at the bottom. Passages between contain heat regenerators. Boeing's lightweight solar concentrator (right) is constructed of aluminum honeycomb.

then can be reinforced with a suitable metal support structure. Use of a single metal reduces thermal distortion that could be expected when the vehicle emerges into sunshine from the earth's shadow. The main limitation of the Fresnel concentrator is the lost area between facets.

A third approach involves the use of rigid reflecting surfaces supported by paraboloidal aluminum honeycomb structure. New jet aircraft use a lot of honeycomb structure because nothing is as rigid per unit weight as honeycomb stabilized with thin sheets on each side. Since the stabilizing sheets carry only a tension load, fiberglass is the best material to use here.

A way of building a paraboloidal concentrator is to make a male master, either by molding from another concentrator, or by grinding and polishing a suitable piece of metal or glass. A parting agent, such as silver, and the reflecting surface, such as aluminum, are vacuum-deposited on this master. The reflecting surface can be backed up by a substrate such as epoxy resin; the structure is built on the substrate by applying epoxy-soaked fiberglass, honeycomb, and more epoxy-soaked fiberglass. Then the whole assembly is cured.

TRW's 'sunflower'

This technique provides high-quality reflecting surfaces that have great mechanical stability. A disadvantage is that the performance of epoxy resin in space conditions has not yet been proven. Also, a paraboloidal concentrator is somewhat difficult to fold. In an approach taken by Thompson Ramo Wooldridge Inc. in its "Sunflower" system, the honeycomb concentrator is cut into truncated pie-sections that are folded like the petals of a flower prior to blooming.

At Boeing, 5-ft diameter concentrators using honeycomb construction are being developed. Because these concentrators are not further collapsed, they have sufficient accuracy to operate thermionic converters requiring as much as 3150 F cathode temperature. Such high temperatures are not practical with segmented concentrators because the segments cannot be aligned with sufficient accuracy. A 5-ft concentrator used in space near earth can produce about 100 watts of electrical output with a high-efficiency thermionic converter. For more power, multiple 5-ft diameter concentrators can be deployed from a spacecraft.

The development of space-use concentrators is costly. It takes several days to make the epoxy-fiberglass-honeycomb layup that is composed of some 30 individually sprayed and cured layers.

On the other hand, the basic materials are cheap. A 3-ft diameter honeycomb concentrator can be made from only $8.20-worth of resin, fiberglass, and honeycomb. After manufacturing is perfected and development costs are written off, the cost of lightweight, high precision paraboloidal concentrators probably will be reasonable. The cheapest 5-ft paraboloidal concentrator today is a surplus searchlight mirror that costs $250 and weighs 160 lbs.

Properly focused, a 5-ft lightweight concentrator can melt holes in ⅛-in. aluminum plate even on a dull day. It is conceivable that these concentrators can be employed for solar cooking in areas where alternate fuels are expensive, or difficult to obtain. They also might be used in point-to-point communication with infrared or even visible light. (When they no longer are useful for concentrating photons, they could slide children down snow slopes! A 3-ft diameter dish weighing less than 2 lbs would have adequate strength for most childen. American ingenuity no doubt will find additional uses for concentrators.)

Heat-to-electricity converters

A solar concentrator-absorber system produces heat energy at a high temperature at the absorber. Thermoelectric and thermionic static converters, mercury turbines, and Stirling-cycle engines are being developed to convert this heat into electric power. (The status of thermoelectric conversion of heat to electric power is discused on page 28.)

The main problem with thermoelectric converters in the past has been that reasonable radiator weight could be obtained only with radiator temperatures so high that overall conversion efficiencies have been in the order of only 1 to 3%. The resulting space power system would have weighed substantially more than an equivalent solar-cell power system.

Thermoelectric conversion systems now being investigated for space use generally have large radiators that maintain low cold-junction temperatures, thereby permiting reasonable conversion efficiency. One concept employs an array of small mirrors; each mirror concentrates sunlight on the hot junction

of a thermocouple that is supported at its cold end by two other mirrors. Thus, the same metal serves as reflector on one side, a radiator on the other side, and as an electric conductor with its volume.

Thermionic converters operate at such high temperatures that radiator area and weight are not significant in the conversion system. (See article on thermionics, page 50.) The problems in the past have been in developing high-temperature vacuum seals that have reasonable life. Nearly all experimental converters built before 1961 failed because of seal leakage, but solutions to the seal problem now are available.

Problems associated with placing a number of thermionic diodes in series within a focal area still have to be solved. At present, each diode generates less than one volt at full load, and a space-use solar thermionic power source is practical only if enough diodes can be connected in series to produce 12 or more volts per converter.

It can be argued that static devices such as thermoelectric and thermionic converters should have better reliability than dynamic converters using rotating or reciprocating parts. On the other hand, well-designed machines with moving parts have demonstrated amazing reliabilities: for example, the compressor of a domestic refrigerator. Furthermore, dynamic energy converters will develop much more power per cubic foot than can present-day static converters.

The most significant dynamic energy converters being developed for space use are mercury turbines and Stirling-cycle engines.

Boiling mercury in a turbine

Early concepts for solar-heated space power plants showed steam engines or turbines and paraboloidal concentrators. Subsequent analysis has shown that steam is not a particularly good working fluid for space use, since waste-heat must be dissipated by radiation. The required area for a steam condenser is too large for practicality.

In contrast, a system employing mercury boiling at 1000 F and 100 psia would require only one-third as much radiator area. Mercury has other advantages. For example, a 40,000 rpm centrifugal boiler-feed pump with a rotor diameter of only 1/3 in. can provide 280 psi pressure and a flow of 40 lb per minute at an efficiency of 35%.

These advantages of the mercury-vapor turbine led Thompson Ramo Wooldridge to begin development of this cycle in 1956. In October 1957, the month when Sputnik I was launched, TRW was awarded a subcontract for development of a mercury turbine with a radioisotope heat source for use in space. Later the development was redirected to a 3-kw unit operating from a nuclear reactor heat source.

Many problems had to be solved in the course of mercury turbine development. For example, useful thermodynamic data about mercury and its vapor were almost non-existent, and had to be obtained by test. The zero-gravity boiling and condensing phenomena were often

IDEAS AND APPLICATIONS #4

Silicon Solar Cells for Terrestrial Use

An electromechanical device promising to unlock an unlimited number of terrestrial applications for silicon solar cells has been developed by the Industrial Products Div. of Hoffman Electronics Corp., El Monte, Calif.

The new system, called the "solar tracker," increases normal power output of solar cells approximately 500%, while ensuring near-perfect output stability over the entire daylight period. It will produce about 16 watt-hours of electricity per day and requires practically no maintenance.

One immediate application for Hoffman's new solar tracker is atop warning buoys in offshore oil fields. The system will charge batteries during the day, and the stored electricity will operate the flashing lights and other devices needed to define traffic lanes.

Other projected applications are telephone relay stations, remote radio installations, and remote telemetering locations.

The solar tracker consists of a servo system and a solar concentrating system integrated into a 14-in. x 3-in. "shadow" panel attached to a reflector shaped like a section of a cylinder. Sensing

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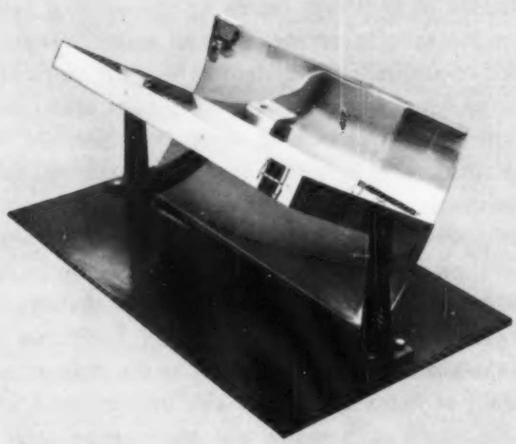


questioned, and only recently were boilers and condensers proved by operation in a temporary zero-gravity environment (during a KC-135 jet airplane flight).

Last year the NASA awarded a contract for mercury turbines for the Sunflower solar-power systems. In the Sunflower concept, part of the heat provided by the concentrator (which opens after launch) will operate the mercury boiler, and the rest of it will melt lithium hydride. When the vehicle goes into the earth's shadow, the mercury will be kept boiling from the latent heat due to freezing of the lithium hydride.

Stirling's red hot engine —30 years early

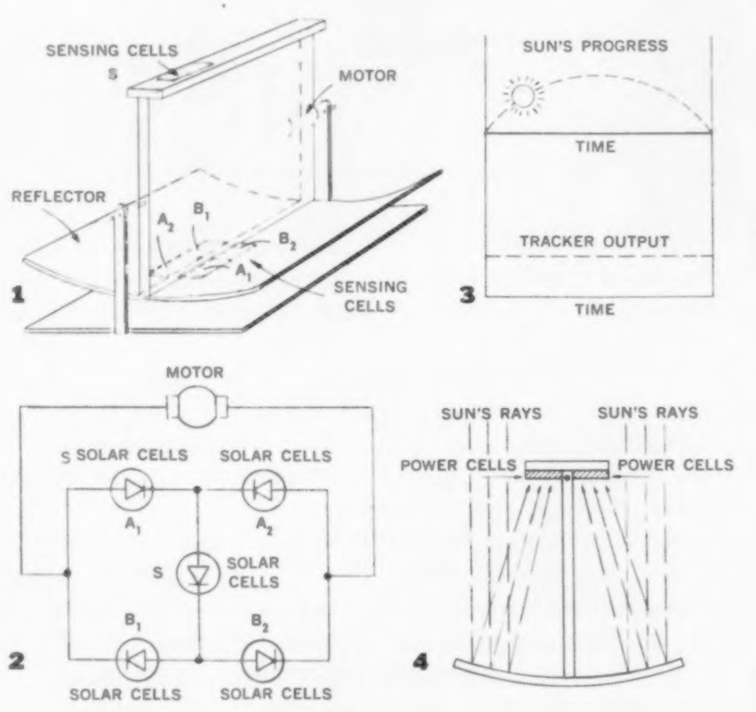
The other significant dynamic converter, the Stirling engine, originally was a closed-cycle, external-combustion, reciprocating heat engine employing regeneration; that is, the working gas did not communicate with the atmosphere, burning took place outside of the cylinder, and the engine had a regenerator that stored heat from one part of the cycle to another.

The Stirling engine was invented by Rev. Robert Stirling, of Dumbarton, Scotland in 1816 when he was 26 years old. There can be little doubt that Stirling was a genius. When he invented his engine, the basic laws of thermodynamics, as developed by Prof. Rankine, Rudolph Clausius, and Nicolas Carnot, were still 30 years in the future; the mechanical equivalence of heat and work was not discovered until 1844 by Joule. To conceive a regenerator for storing heat from one part of the cycle to the next in the year 1816 was a real breakthrough.

Lack of thermodynamic knowledge caused the decline of the Stirling engine in the 19th century. Stirling insisted that his engine required heat only to make up radiation, conduction, and convection losses. He did not realize that heat input had to include engine heat losses, as well as the thermal equivalent of the engine's power output plus the cycle losses. Thus, Stirling made his cylinder heads smooth for minimum heat transfer. To keep the engines running with this poor heat-transfer arrangement, operators had to keep the cylinder heads red hot. As a result, the cast-iron cylinder heads would crack after a few years of operation.

Thousands of engines employing the Stirling cycle and modifications of the cycle were built in the late 1800s. The regenerators were abandoned for the sake of simplicity, at the cost of weight and efficiency. One 0.9 hp engine weighed two tons and had 1.4% efficiency. The engines were bought only because they were quiet and required no boilers. The era of the old air engines ended in 1939 when the last one was made by the Kessler Co., of Chicago.

Yet even before the death of the



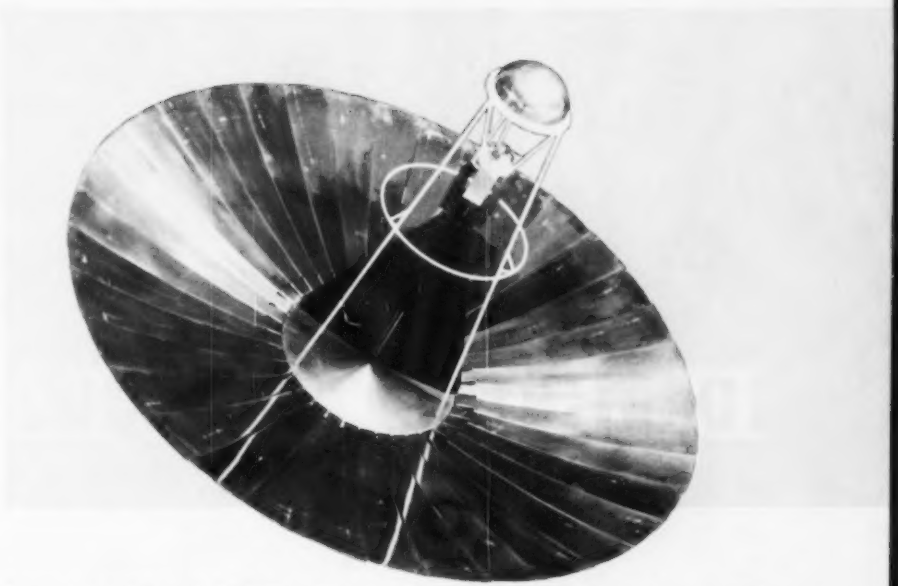
solar cells are located on top of the panel and on each side of its base attached to the reflector (see diagram 1).

As long as the sun's rays are distributed evenly over the shadow panel, the tracker does not move. But as the sun moves across the sky, the pattern of light rays falling on the sensing cells shifts. This causes the cells to activate a small motor, attached to the panel, which re-positions the system so that the sun's rays again are distributed equally across the sensing solar cells (diagram 2). In this manner the system, and most important, the reflector, always faces the sun for maximum output and stability (diagram 3).

The reflector is shaped so that it concentrates the sun's rays onto silicon power solar cells located underneath the ridge at the top of the shadow panel (diagram 4). The solar energy hitting these cells is four to five times that of normal sunlight, greatly increasing the power generating capability of the cells. Additional heat dissipated by the power cells is carried off by the shadow panel.

The output of the solar tracker can be increased simply by extending the length of the panel and adding more solar cells. ■

During his 12 years at Boeing, Henry Oman has designed and tested electric power systems for airplanes, preliminary design missiles, and space vehicles. He has been working on the generation of electric power from electrochemical, solar, and nuclear sources since 1956.



SUNFLOWER *solar mercury Rankine power conversion system has been developed by scientists in the TAPCO group of Thompson Ramo Wooldridge.*

old engine, the rebirth of the Stirling cycle had started. The N. V. Philips Laboratories, Eindhoven, Netherlands, was looking for a quiet, efficient, portable engine for powering electronic equipment in remote regions. Philips' scientists spent years in thermodynamic analyses and mechanical design. For example, configurations such as opposed piston, V-type, and radial engines were considered and then abandoned in favor of the original design invented by Stirling 140 years before! Modern technology was applied to heat exchangers, gas flow dynamics, seals, and regenerators. Use of high-pressure hydrogen instead of air for a working fluid solved lubrication problems and improved engine efficiency to an amazing 40%.

Combustion air not required

The Stirling engine can be used in space power plants because it doesn't require combustion air. It doesn't matter if the heat source is a blow-torch, concentrated sunshine, or nuclear heat. The high cycle efficiency is important because it means small solar concentrators and small waste-heat radiators. The Stirling engine has no internal combustion or explosions, and the mass of the reciprocating parts can be counterbalanced to a precision where there is no perceptible vibration. Torques can be balanced by the use of contra-rotating generators.

Solar-heated Stirling-engine power sources for space application are being developed currently by the Allison Div. of General Motors Corp. under U.S. Air Force sponsorship. A preliminary design of a 3-kw power source for satellites shows a weight of 567 lbs. This weight includes a 19-ft diameter solar concentrator, a 160-sq ft waste-heat radiator, and a 45-lb lithium-hydride heat reservoir. The 567 lbs compares with an estimated 700 lbs for a mercury-turbine system, and more than 1,000 lbs for equivalent silicon solar cells and batteries.

The only problems in applying the solar-heated Stirling engine to space use are reliability and lubrication in a zero-gravity environment.

Solar power on earth?

Predicting future uses for solar space-power plants can be dangerous. None of the 1954 to 1956 predictions for silicon solar usage were for space application; yet today whole industries have been built for supplying solar-cell panels for that purpose.

It will be interesting to see which solar power system turns out to be the best for space application. The dynamic and static systems employing solar concentrators all offer hope for low weight and reasonable cost. On the other hand, silicon solar-cell power supplies are working in space today, and improvements in performance and reductions in cost undoubtedly will come. Combining solar cells with a simple Somor concentrator, which requires only modest orientation, could extend the usefulness of solar cells considerably.

Scientists always find it difficult to justify solar power on earth surface use. Some $350,000-worth of high-efficiency silicon solar cells will generate one kilowatt of electric power when sunshine is available. The same kilowatt produced by conventional generation costs one cent an hour (in the Pacific Northwest), or $87.60 if consumed continuously for a year, day and night.

Yet if high-performance low-cost equipment becomes available, new uses for solar power plants undoubtedly will be found. Use of cheap, low-efficiency solar cells with Somor concentrators certainly would make solar-cell power economically applicable where high-efficiency cells by themselves are marginal. Uses also could be found for high-quality concentrators and mechanical and thermionic conversion apparatus if they became low enough in cost.

The heat-energy converters will be useful in fields other than solar energy conversion. The knowledge about the mercury-turbine cycle gained during space-power research will be useful in designing liquid-metal cycles for nuclear plants.

The Stirling engine appears promising. Today the fuel-burning Stirling engine is heavier than the gasoline automobile engine for the same power, but for equal output it burns only about half as much fuel. Its outstanding characteristic is silent operation; the noisiest component is the burner. Low maintenance cost would be expected to result from the absence of combustion products and oxygen in the combustion chamber, and the absence of an ignition system.

There can be no doubt that more and more energy needs of mankind will be derived from conversion of solar radiation to power. The supply of fossil and nuclear fuels on earth is limited, and as these supplies are depleted, costs will rise. The cost of sunshine remains constant—it's free. ■

ELECTROSTATIC POW

'And the First Shall Be Last'

THE FIRST METHOD of generating electricity was probably frictional, and as early as the 7th century B.C. Greek philosophers were aware that rubbing amber gave it the property of attracting light objects. On the other hand, chemical cells that might have been used for electroplating have been found near Baghdad in the ruins of the Parthian Kingdom (250 BC to 224 AD).

Irrespective of which method of generation was first known to man, there is no doubt that the first machine generators of electricity were electrostatic. These appeared in the 18th century and charge separation was again accomplished by friction. Except for the various forms of frictional induction machines devised in the 1860s, no significant improvements were made in electrostatic generation until about 1932.

Progress was not faster because it was not appreciated that high dielectric strengths (the ability of the insulating medium to withstand high electric fields) are required if machines generating by electric field variations are to be compact. Thus, when the great need for power developed in the 19th century, the electrical industry concentrated its attention on electromagnetic machines.

A renewed interest in electrostatic power developed with the invention of the belt machine by R. J. Van de Graaff in 1932. In this machine, charge is sprayed onto a moving dielectric belt that carries it to a terminal where a high potential is developed. The belt normally operates in a compressed gas to provide high dielectric strengths. The Van de Graaff generator, of course, is now an important tool of the nuclear physicist.

In the late 1930s, A. F. Joffe and B. M. Hochberg in Russia were active in developing rotating electrostatic machines. It is difficult to assess the success of their efforts, but one of their many machines was 13 ft high and apparently incorporated a successful vacuum tube for one-million volts.

Since about 1942, much research on rotating electrostatic machines has been conducted in France at the University of Grenoble under N. J. Felici. This work led eventually to the development of rotating dielectric cylinder generators, produced by the French company, Société Anonyme de Machines Electrostatiques, for voltages up to 600 kv.

High dielectric strengths

In general, high-pressure gases have been used to provide high dielectric strengths in electrostatic machines. Other approaches use liquid dielectrics and high vacuum. Unfortunately, liquid dielectrics obviously limit machine speeds and so far exhibit unattractive ionic conductivities.

This leaves high vacuum, which has been stated to be both "promising" or "unpromising" by various experimenters. With the need for power conversion equipment in space where very low pressures exist, and with advances in vacuum technology, the vacuum insulated

ER FOR SPACECRAFT

electrostatic generator definitely has become the most promising.

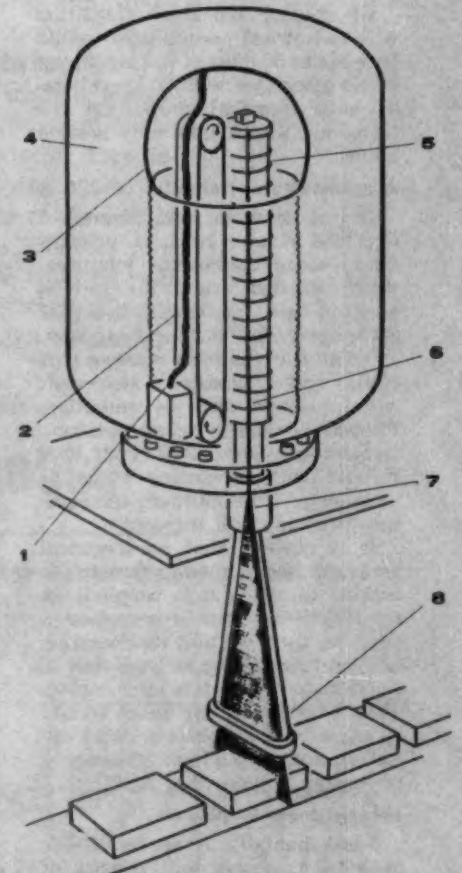
As with other non-conventional power conversion devices, development of vacuum electrostatic generators is being accelerated by the growth of space technology. Large powers, of the order of megawatts, will be required (probably early in the 1970s) for the electrical propulsion of manned spacecraft on more distant missions, such as to Venus and Mars. The source of this power almost certainly will be thermal energy from a nuclear reactor which will be converted to electrical power by either a static or a dynamic system.

Static systems, such as thermionic and thermoelectric converters, most likely will be the most suitable means of converting large power in space eventually. However, such systems have far to go and serious problems remain to be solved. It is likely that, for an appreciable time before static systems are available, megawatt powers in space will be achieved with dynamic systems.

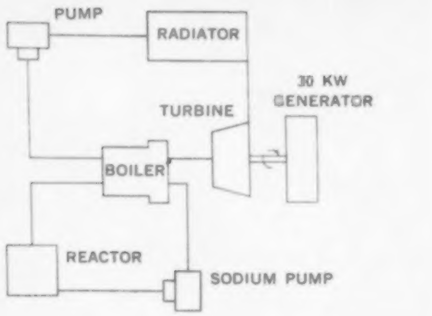
Dynamic power systems

To appreciate the qualities of electrostatic generators that make them attractive for space use, it is first necessary to examine the requirements of both dynamic space power systems and of the loads which they have to supply. For example, the National Aeronautics & Space Administration's SNAP 8 system (diagram 1, page 72) will develop 30 kw in the initial stages and probably will be the first reactor system to go into space.

ELECTRIC CHARGE *sprayed on a rapidly moving insulating belt (1 and 2) initiates the operation of a Van de Graaff electron accelerator. The charge transfers automatically from the belt to the terminal (3), thereby establishing a high potential. An atmosphere of compressed nitrogen insulates the terminal to prevent arc-over (4). A very high vacuum glass and metal tube (5) provides the only path for the electrons to escape from the cathode. Electrons are accelerated to high velocities (6). The electron beam then is scanned by magnetic coils (7) to cover the product passing beneath. Dosage of the radiated product (8) depends on the speed of the conveyor belt, energy of the beam, and width of the scan.*



by **Dr. Sam V. Nablo,** *manager of electrical propulsion,*
and **Dr. A. Stuart Denholm,** *manager of power conversion, Goodrich-High Voltage Astronautics Inc.*



A later version of SNAP 8 will use two turbogenerators with the reactor to develop 60 kw, which, using electrical propulsion, could boost a 9,000 lb spacecraft from a 200-mile orbit to a 22,000-mile (or 24-hour) orbit. This spacecraft could be placed at a 200-mile orbit by the Atlas/Centaur combination, and it is estimated that the electrical propulsion approach would place a larger payload in the 24-hour orbit than a chemical propulsion system—and more cheaply.

Of course, the orbit transition with electrical propulsion would take about 60 days at the low thrust levels associated with 60 kw, whereas with chemical propulsion the transition would take only several hours.

A massive heat sink

It can be seem from diagram 1 that the reactor heats a primary fluid (sodium-potassium mixture), which in turn heats the turbine working fluid (mercury) via a heat exchanger. The turbine heat sink, a radiator, is the most massive part of the system because a spacecraft can lose heat only by radiation. Present systems have an optimum radiator temperature of about 1200 F, and with advancing materials technology this optimum temperature probably will increase.

It is obvious that an electrical generator has to operate close to the turbine to which it is coupled (in the SNAP 8 system it is contained *with* the turbine) and its operating temperature will be at least that of the radiator unless it is force-cooled. Thus a generator for space should be capable of high-temperature operation and have a high efficiency—preferably approaching 100%.

Interplanetary power

Fundamentally, a space vehicle propulsion system will consist of the nuclear heat source, power conversion equipment, and thrust device contained within an integrating structure. For the types of missions now under study, mainly capture or impacting programs to Venus and Mars, the dominant power demand arises in the propulsion system itself. As a result, some appreciation of the types of propulsion systems suitable for these missions is necessary in order to view the supply requirements in the proper perspective.

Propulsion systems for space vehicles are broadly classified as chemical or electrical, depending upon the principle of operation of the rocket. But a more meaningful classification would be energy-limited or power-limited. In energy-limited systems, the total amount of energy is the dominant design factor, while in power-limited systems, the level of power production predominates.

Thus, for the chemical system, the propellant available is proportional to total energy stored in the engine, whereas nuclear or solar supplies are limited by the direct dependence of their masses on the power they produce. Into which realm do interplanetary vehicle requirements fall?

Interplanetary missions demand large velocity increments of a spacecraft in order to obtain a practicable trip duration. Thus, large exhaust velocities are required from the engine, and the nuclear source must deliver a large and sustained output of electrical power. As a result, space propulsion systems are power-limited. Their performance will depend very sensitively on the specific power figure for the primary supply.

Electric thrust engines

Electric thrust engines now under study generally fall into three categories which may be characterized by a specific impulse (a thrust developed per unit of propellant mass exhausted):

- *Electrothermal* thrust units have been developed at low specific impulses (less than 2,000 seconds) to practicable efficiencies and thrust levels. In principle, the propellant gas is heated by an electric arc to extremely high temperatures and then exhausted through a nozzle.
- *Electromagnetic* devices have shown considerable promise in the medium specific impulse range (over 2,000 seconds), but are far from flight status. Such engines involve the acceleration of a conducting plasma by magnetohydrodynamic techniques. As such, they represent inherently heavy devices of low power efficiency. Recent advances in the development of high-permeability low-density magnet configurations suitable for MHD applications could bring this approach to a useful level of performance before the end of this decade.
- *Electrostatic* systems have been developed for high specific impulse engines (greater than 5,000 seconds) to the point where low-thrust flight prototypes are now available—that is, engines developing less than 0.1 lb of thrust.

Electrostatic units are essentially high-current ion sources possessing good propellant and power efficiencies wherein charged particles (usually in ionic form) are accelerated in a single potential gap to the desired velocity. Power efficiency of electrostatic devices is significantly greater than either of the others, and can approach 100% in a well-designed unit operating at higher specific impulses (over 20,000 seconds).

However, a problem peculiar to this engine has not yet been resolved completely and will be the prime goal of the first engine flight tests performed in next year's ballistic shots. This is the vehicle neutralization problem: since charged particles are being expelled as the propellant (through electrostatic acceleration), a net charge will remain on the vehicle which must be neutralized to assure that no concomitant beam instability or thrust loss occurs.

NASA plans to use electric engines in spacecraft for Mars and Venus probes and orbiters and probes to the sun, Mercury, and Jupiter. The first electrically propelled spacecraft flights are scheduled for 1963 using the Atlas/Centaur booster. More ambitious missions using the Saturn booster are planned for later in the decade.

Of space power sources under development, the SNAP 8 supply has been used in most mission analyses. This unit, designed in one version to deliver 60 kw electrical output at a specific power of 0.02 kw per lb, has a nominal lifetime of 415 days. These specifications for the first true space power system limit useful thrust when total flight time becomes a consideration.

Mission to Mars

A practical application of the electrical vehicle is the Mars orbiter. The spacecraft would be launched into a 1,000-mile orbit by an Atlas/Centaur booster. The electric engines then would take over, providing sufficient thrust for a slow spiral orbit out from the earth with escape effected at approximately the distance of the moon from the earth. A sustained thrust would result in a transfer to a Mars orbit. Once in orbit, the engines would be turned off to permit data transmission with the remaining available power.

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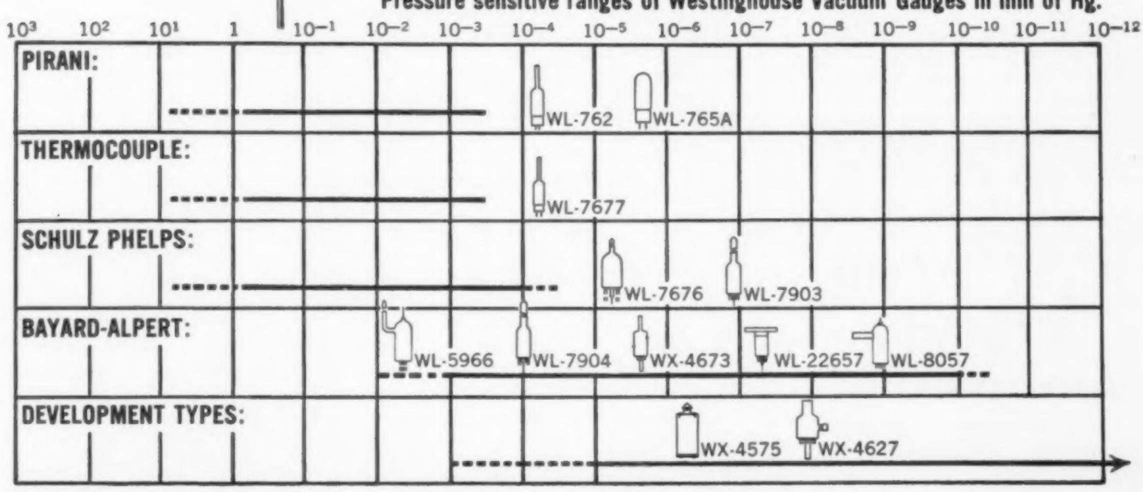
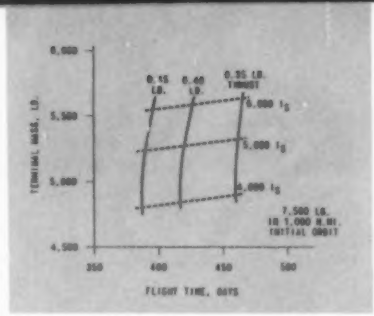




Some indication of terminal mass of the spacecraft in a 500-mile orbit around Mars—after launching from an initial 7,500-lb system mass in a 1,000-mile terrestrial orbit — is shown in diagram 2. These calculations, made at the Jet Propulsion Laboratory, are valid to within 10%.

The following conclusions are evident from the calculations: flight time depends primarily on thrust, whereas terminal mass depends primarily on specific impulse. Now the thrust is limited by the powerplant itself; hence, an engine thrust of at least 0.4 lb must be provided for the mission. Since the total powerplant and thrust system will weight some 4500 lbs, a specific impulse of at least 4000 seconds must be provided to yield a useful payload weight.

The summary below of several interplanetary mission analyses executed at JPL yields a useful prognosis for system requirements through this decade. The gross payloads delivered are the terminal mass minus the powerplant mass.

While the analyses are preliminary, they show the severe reliability and lifetime requirements imposed upon an electrical propulsion system for interplanetary missions. The role of materials research in developing useful interplanetary vehicles cannot be overestimated.

The range of specific impulse required of the electric engine for these missions clearly indicates the necessity of electrostatic thrust devices capable of sustained operation at medium specific impulse; that is, below 10,000 seconds.

Project Rover

Another type of advanced propulsion system that has been less extensively studied is the direct nuclear system now being developed under the AEC-NASA-sponsored Project Rover. The schedule calls for experimental flights in 1966 to 67 with the ultimate goal of developing a nuclear third-stage engine compatible with the Saturn booster.

This system is comparable to the electrothermal, except that the working gas (hydrogen) is heated to high temperatures in the reactor core and expands through a nozzle to provide specific impulses in the range of 1,000 seconds. (The most energetic chemical propellants are theoretically capable of specific impulses up to about 400 seconds.)

The direct nuclear system is capable of high thrust and accelerations several orders of magnitude greater than foreseeable ion-electric engines. The two systems have comparable terminal mass yields with a slight flight time advantage lying with the nuclear rocket. Higher energy missions such as a Jupiter flight demonstrate a clear-cut advantage for the nuclear-electric (ion) approach.

High efficiency nuclear-electric power sources in the one megawatt range will be in demand by the last half of this decade. The development of high-performance boosters such as Saturn and the realization of reliable electric engines capable of high specific impulse thrust in the 0.1-lb range will prove to be sterile accomplishments without the

Mission	Powerplant	Thrust	Specific Impulse	Mission Time	Gross Pay Load
Lunar orbit	60 kw	0.4 lbs	5,000 sec	200 days	4,500 lbs
Venus capture	60	0.4	5,000	360	4,000
Mercury capture	1,000	7.0	5,000	250	21,000
Jupiter capture	1,000	4.0	10,000	650	22,000
Saturn capture	1,000	4.0	10,000	800	15,000

As manager of the power conversion group at Goodrich-High Voltage Astronautics, Dr. A. Stuart Denholm (left) is responsible for the development of electrostatic generators for space vehicles. Prior to joining GHVA, he spent five years with the National Research Council of Canada examining various high voltage problems, including corona and radio interference. A graduate of the Royal College of Science & Technology, Scotland, Denholm obtained his PhD from the University of Glasgow. Dr. Sam V. Nablo (right), manager of GHVA's electrical propulsion group, has been engaged in the study of electrostatic thrust systems since the early days of the program. He previously performed research in the nuclear field. Nablo received his PhD from McMaster University, Hamilton, in beta- and gamma-ray spectroscopy.

primary power systems necessary for the achievement of these difficult interplanetary missions.

Vacuum electrostatic generators

For convenience, electrostatic generators may be classified as charge transfer machines and variable capacitance machines. Electrostatic generators now available commercially are of the charge transfer type and are used as convenient tools for developing high voltages rather than for power conversion—although in principle they *are* mechanical to electrical power converters.

The variable capacitance forms of machines were examined at some length by J. G. Trump and R. J. Van de Graaff in the early 1930s. At that time, Trump demonstrated that they were almost 100% efficient. It is the variable capacitance generator, which has never had commercial exploitation, that is being investigated as a promising power conversion device for space, particularly because of its simplicity and its possibility for brushless operation.

The variable capacitance machine is simple in principle. If voltage is applied across the plates of a capacitor, a force is developed that tends to draw the plates together. Basically, this happens because applying a voltage across a capacitance is the same as placing a positive charge on one plate and a corresponding negative charge on the other plate, thereby developing an electric field between the plates.

When the plates are moved apart against the electrostatic force, an exchange of energy takes place between the mechanical driving system and the circuit maintaining voltage across the plates. Correspondingly, if the plates are allowed to collapse, they can do physical work at the expense of the energy in the circuit maintaining the voltage.

Hence, it can be seen that there is a generating action as the plates are moved apart (capacitance decreased) and a motoring action as

they are moved together (capacitance increased).

If the same voltage is maintained, both with increasing and decreasing capacitance, the net exchange of energy is ideally zero. However, by suitably varying the voltage in the cycle of capacitance change, a net generating or motoring action can be developed. A pulsating capacitor is not a convenient form mechanically, and rotary machine configurations not unlike a rotary tuning capacitor are used to obtain capacitance cycling.

100% efficiency

An a-c form of this machine—which is similar in operating characteristics in many respects to the electromagnetic synchronous machine—is simplicity itself. An early working model used by Trump to demonstrate near 100% efficiency is shown below.

The almost perfect efficiency is achieved because the loss mechanisms which can exist in the vacuum electrostatic machine are weak. *Electromagnetic* generators can be better than 90% efficient, the losses being due to hysteresis and eddy currents in the iron, copper losses in the windings, and bearing friction and windage. The vacuum insulated *electrostatic* machine obviously has no windage loss, no iron loss, and negligible copper loss, since relatively small currents flow in the massive blades as the charges are redistributed during the cycle of capacitance.

Simple circuits using rectifiers can be used to make the vacuum insulated machine develop direct voltage, and these rectifiers can be incorporated in the machine structure itself, since it is a high-vacuum device. In fact, electronic commutation is one method of producing a brushless machine.

As far as a rectifier is concerned, there is no change in the action if either the anode or the cathode spins. The first d-c vacuum electrostatic machine, which developed about 150 watts at 10 to 20 kv and confirmed convincingly the theory of such circuits (before being mounted for posterity), is shown below.

It already has been noted that high field strengths have to be developed in electrostatic machines to make them compact, and the choice was between high-pressure insulation and high vacuum. Currently, high-pressure insulation is a more reliable insulating medium at very high field strengths than high vacuum, but it has to be excluded because of the prohibitive windage losses associated with the high operating speeds of space power systems, for example, 24,000 rpm.

Experiments show that a one mm gap vacuum can insulate at least as much voltage as, for example, hydrogen at 50 atmospheres. Improvements in insulation strength are most significant since doubling the electric field strength increases the power from a given machine by a factor of four.

Lubricating in space

For a machine to be driven in space, the problem of shaft sealing and bearing lubrication must be solved. There is now great interest in dry-film lubrication of bearings primarily as a solution to high-temperature, high-speed operation. Such films have been used in vacuum-insulated electrostatic generators with encouraging success. Otherwise, it is possible to seal bearings with a suitable lubricant if a satisfactory seal is available.

At one time, shaft sealing was considered a greater problem than it is now. This optimism is due in part to some encouraging results from ground operation into vacuum systems with small pumping capacities using face seals, and the realization that in space some leakage can be tolerated—it will hardly raise the pressure!

The vacuum-insulated electrostatic generator is being developed as a serious contender for power conversion in space, particularly for those large loads associated with electrical propulsion. Electrostatic generation normally is associated with very high voltage generation. Yet this form of machine can develop power effectively at voltages as low as 5 kv, and possibly lower.

On the other hand, it can develop potentials approaching a million volts. Perhaps of more significance is the generator's high efficiency and suitability for high-temperature operation which allows flexibility in the design of the other component parts of the power system.

Terrestrial dividends

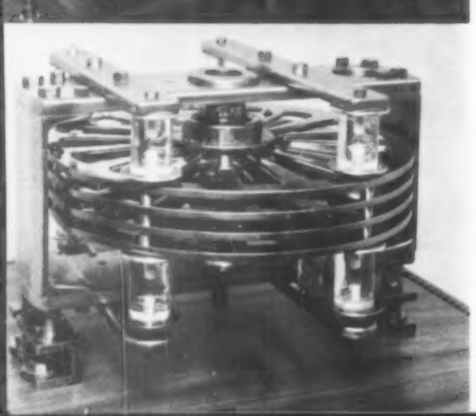
What significance has the vacuum-insulated generator program for industry?

Secondary benefits include advances in the knowledge of support and sealing devices for high-speed rotation in vacuum and of vacuum insulating strength. Since the generator develops large powers at high voltage, it may find many applications in the fields of nuclear physics and radiation processing.

In that event, the generator is doubly attractive, because it is a vacuum-insulated device and can be integrated with various kinds of particle accelerators and analyzers that also operate in vacuum.

There also is the possibility of generating for high-voltage d-c transmission, which has many attractions for extra-long-distance power transmission and the interconnection of independent networks.

In 1933, J. G. Trump envisaged the generation transmission and switching of large powers using vacuum insulation throughout. The vacuum switch is now an accomplished fact used on many systems for capacitor switching. Strangely enough, its main disadvantage is that it switches too well (too quickly). Perhaps vacuum-insulated generators someday will appear alongside vacuum-insulated switches. ■



THE MARK I *(upper left) is an experimental vacuum-insulated electrostatic generator developed in 1932 by Dr. J. G. Trump. First machine of its type, it delivered 60 watts at better than 99% efficiency. Vacuum insulated generators are expected to become serious contenders for power conversion in space. The Mark II generator (lower left), developed by Goodrich-High Voltage Astronautics, delivers 150 watts at 20 kv, yet it also can develop power at voltages as low as 5 kv.*

Long lead time is essential to the development of large nuclear space power systems. Present methods of power generation would require an impractical heat rejection surface nearly the size of a football field for a power output of one megawatt—power which will be needed for critical space missions already in the planning stage.

Garrett's AiResearch Divisions have now completed the initial SPUR design studies and proved the project's feasibility to supply continuous accessory power and low thrust electrical propulsion in space for long periods of time.

Cutting projected 1 MW power systems to 1/10th the size and 1/5th the weight of present power systems under development will be possible because of SPUR's capability to operate at higher temperatures, thereby sharply reducing the required radiator area.

Garrett has been working with the Air Force and the Atomic Energy Commission on SPUR as the prime contractor for more than one year and has more than five years of experience in space nuclear power development. Also an industry leader in high speed rotating machinery, heat transfer equipment, metallurgy and accessory power systems, the company is developing design solutions for SPUR in these critical component system areas.

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AiResearch Manufacturing Divisions

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by **Dr. Charles E. Crompton,** *director, nuclear chemistry dept., The Martin Co.*

ISOTOPIC POWER

A MAJOR SPACE FEAT was scored by the United States on June 29, 1961, when the world's first nuclear-powered space system, the Navy's Transit navigation satellite, was launched successfully. Even more recently, the world's first radioisotopic-fueled weather station was installed in the Arctic by the Atomic Energy Commission. With these achievements, a fascinating new method of generating electricity became available to man: isotopic power.

The tremendous strides made in miniaturization of circuits has focused attention on a companion need for small, durable, reliable, electrical generators in the range of one to 500 watts that will power sensing devices and telemetering equipment for long periods of unattended operation.

These atom-fueled generators operate with no moving parts. Heat energy is derived from the decay of radioactive isotopes and is converted directly to electricity. Such generators possess lifetimes dependent only upon the gradual decay of their radioactive heat sources.

The advent of these unique devices has sparked interest in their use as sources of power for diverse equipment in remote regions of the earth or in space. The isotopic-powered generator in the Transit, for example, is capable of providing continuous power for years.

Yet, for many purposes, continuous power is not required and these power systems may be coupled to battery packs to deliver pulses of electrical power during the duty cycle. Meteorological data-gathering stations and remote radio beacons and warning devices can use pulsed power sources.

The plutonium-powered SNAP

A non-fissionable form of plutonium is used as fuel in the SNAP (Systems for Nuclear Auxiliary Power) generator designed and built by The Martin Co. for the AEC to provide continuous power in the Transit satellite. The Transit system is being developed for the U.S. Navy by the Johns Hopkins Applied Physics Laboratory, Howard County, Md. Heat released by spontaneous decay of plutonium-238 is transformed directly into electrical energy by a thermoelectric system. A white coating on the generator helps it radiate excess heat and cuts down the amount of heat energy absorbed from the sun's rays.

Shaped like an elongated sphere, the SNAP generator powers the satellite's instruments and two of its four transmitters. Solar cells power the other two transmitters. The lightweight, compact generator is only about 5 in. in diameter and 5½ in. high.

The SNAP generator in Transit is similar in concept to the SNAP-3, the first practical radioisotope-fueled generator revealed in January 1959 by President Eisenhower. The SNAP-3, weighing four lbs, produced 3.3 watts at an efficiency of 5.5%. Heat from the fuel, 0.38 gram of polonium-210 (an artificially produced radioactive material), was converted to electricity by 27 thermoelectric couples made of lead telluride. Minnesota Mining & Manufacturing Co., St. Paul, supplied the original thermoelectric converter.

SNAP-1A, another generator, is considerably larger (34 in. high and 24 in. in diameter). It is designed for fueling with the radioisotope cerium-144, and would provide a minimum of 125 electrical watts for one year — after which the power gradually would diminish. Although SNAP-1A has undergone extensive environmental and electrical checkouts, it is being used as a test bed for advanced development and is not now scheduled for fueling.

Strontium weather station

For the past 20 years, weather bureaus all over the world have sought to improve automatic weather stations that would operate unattended for long periods of time. In all previous case, stations were battery-operated and failed after a few days or weeks or, in some cases, months. If meteorological information could be obtained regularly from the polar regions, deserts, mountains, tropics, and oceans, existing gaps in data would be eliminated; vastly improved 72-hour forecasts and five-day outlooks would result.

Like the SNAP generator now beeping signals from the Transit, the atom-powered weather station recently installed on barren Graham Island in Canada's Northwest Territories was developed for the AEC at Martin's Baltimore plant. Unlike the satellite generator, the unmanned weather station is powered by heat from safely-enclosed pellets of strontium-90. The heat is converted into a continuous five watts of electricity by a series of thermoelectric couples. This electricity is stored in rechargeable chemical batteries until time for transmission: every three hours.

Year-around observations from polar regions are now possible for long-range weather prediction. Capable of transmitting over distances up to 1500 miles, the radioisotope-fueled power system uses no moving parts, sustains no wear, and offers long-term maintenance-free reliability.

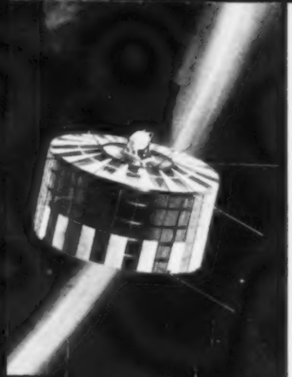
Rejected heat for warmth

The electrical generator and data recording and transmission equipment are shown at right. About 95 watts of rejected heat is used to warm the instrumentation since this enclosed weather station (26-in. diameter, 8-ft high) is exposed to Arctic temperatures.

All operations of the station, including shutdown, are controlled by a sequencer after initiation by the station master timer. Two 460-watt peak output signals on two separate radio frequencies are provided by the transmitter. All weather information is translated into a digital code for reliability and ease of transmission.

A floating boat-type strontium-90-powered weather station is now being produced for the Navy and the AEC, and a radioisotopic generator (Sr-90) is under construction for the Coast Guard and AEC to power a navigational light buoy.

Since its discovery, the energy of radioactive decay has captured scientific imaginations. Unstable ra-



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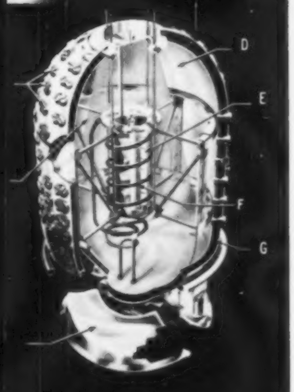

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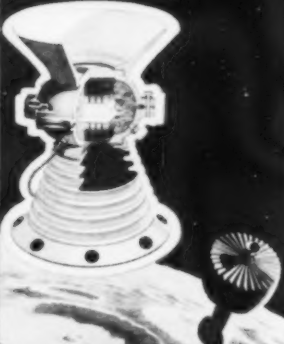

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*Conversion of heat energy from the decay of radioactive isotopes is providing man with a new source of power. Paving the way is the world's first nuclear-powered space system, the Navy's Transit satellite (**1**), successfully launched in June. The white sphere on top of the satellite is a radioisotope-fueled SNAP generator built by The Martin Co. A cutaway drawing of the 125-watt SNAP 1-A generator, undergoing preliminary tests at Martin's Nuclear Div. (**2**) shows: (a) thermoelectric couples, (b) radiant heat reflector, (c) heat shutter, (d) space for liquid mercury shield, (e) cerium-144 pellets, (f) cooling coils used in ground handling, and (g) insulation. The world's first nuclear-powered weather station (**3**) has been installed in a barren area north of Canada. The atomic generator at the bottom of the cylinder, deriving power from pellets of strontium-90 via a thermoelectric conversion system, operates the electronic instrumentation and automatically transmits weather data every three hours. A radioisotope-fueled lighthouse beacon (**4**) developed for the Coast Guard is one of several navigational devices now being powered by nuclear energy. Artist's concept of a lunar impact mission vehicle (**5**) shows a cutaway of an isotope-powered thermoelectric generator proposed for the space vehicle.*

dioactive atoms release their energy in one or more of three distinct types of radiation: alpha, beta, and gamma rays. Alpha and beta rays are particulate in nature and are not penetrating: that is, they give up their total energy within a very short distance of their origin. Gamma rays are penetrating electromagnetic radiations similar to x-rays.

When an intensely radioactive material is confined in a sealed capsule, these radiations dissipate their energy in the surrounding containment material, thus raising its temperature. Selected isotopes can produce high temperatures and power densities (watts per gram) limited only by material melting and heat transfer constraints. Such radioactive sources typically are made into high melting-point compounds (oxides or carbides) to serve as heat sources.

Two major types of radioactive source materials useful in direct conversion generators stem from the control of nuclear fission. First, the splitting of uranium atoms within a reactor leads to production of about 200 radioactive fission products previously considered waste. By 1965, it is estimated that radioactive energy of fission products generated in all U.S. reactors will equal two-million watts of power. Of course, only a small fraction of this energy may be in a form suitable for use in isotopic power generators.

The second type of radioactive source materials are chemical elements not normally included among fission products. Such elements are made artificially radioactive in a nuclear reactor by exposure to neutrons.

Radioisotopes of either type used as a heat source must be selected judiciously on the basis of several criteria: power density, safety, radioactive half-life, cost, and availability. Power density (watts per gram), for instance, is used to compute the maximum temperature that may be achieved by the heat source.

This operating temperature is very important in determining efficiency of the energy conversion device employed since no heat engine

operating between two given temperatures can be more efficient than a perfectly reversible engine operating between the same temperatures (the Carnot theorem).

Avoiding external radiation

Since gamma radiation is penetrating and biologically harmful in large doses, gamma-emitting heat sources must be shielded with lead to minimize hazards both to personnel and to sensitive electrical components or film. This external radiation problem may be avoided through use of an alpha emitter as the radioactive source material.

Alpha emitters are particularly toxic if ingested into the body. For safety, therefore, it is imperative that alpha-emitting fuel be an insoluble chemical compound and that containment of this material be permanent to preclude dispersement in our environment.

Isotopes produced by reactor irradiation, particularly alpha emitters, offer higher power densities, higher operating temperatures, and reduced shielding requirements. Extensive examination of available alpha emitters shows that three of them have outstanding merit as heat sources. These appear in the table below with several other important isotopes whose characteristics are noted.

small heat source, the fuel must have a power density in excess of 0.01 watt per gram.

Having selected a safe, small, intense heat source of radioactive material, let us examine the two direct conversion systems employed: thermoelectric and thermionic conversion.

Low-temperature converters

The conversion of heat produced is a problem quite independent of the radioactive fuel. For devices operating in the range of one to several hundred watts, direct conversion is accomplished most efficiently and conveniently by the thermoelectric method. *(See "Thermoelectricity," page 28.)* The principle involved is that upon which the bimetallic thermocouple was devised. In 1821, T. J. Seebeck discovered the phenomenon that arises when two dissimilar metals are joined in a closed loop and one metallic junction is heated with respect to the other. The result is a small voltage between the two junctions, accompanied by a flow of electrical current.

The discovery and improvement of semiconductors is responsible for the current prominence of thermoelectric conversion. With today's semiconductor materials (such as lead telluride) for a pair of "positive" and "negative" thermoelements, a 700 F temperature differential will produce about 0.1 to 0.2 volt and will allow a current of one ampere to flow. For comparison, a conventional bimetallic thermocouple will produce a few millivolts and negligible current under the same temperature conditions.

RADIOISOTOPE HEAT SOURCES

Nuclide	Mode of Decay	Half-Life	Fuel Compound Form	Attainable Thermal Power (watts per gram)	Estimated Cost (dollars per watt) Current	Projected
Po-210*	Alpha	138 days	Po	142	$300	—
Cm-242*	Alpha	162 days	Cm_2O_3	120	80‡	$ 45‡
Pu-238*	Alpha	86.4 years	PuC	0.55	—	1600
Co-60*	Beta, gamma	5.3 years	Co	0.30†	210	60
Ce-144**	Beta, gamma	285 days	CeO_2	4.8	87	14‡‡
Cs-137**	Beta	33 years	CsCl	0.08	500	54‡‡
Sr-90**	Beta	28 years	$SrTiO_3$	0.10	455	23‡‡

**Produced by reactor irradiation*
***Fission product*
†At a specific activity of 30 curies per gram
‡Irradiation cost not included (increase at $100 per watt)
‡‡AEC estimates based on construction of separation facility

Of the 200 fission products formed, many have such short half-lives that they are useless. *(At the end of each successive half-life period, the quantity of isotope remaining is half the amount present at the beginning of that particular interval. Hence, after two half-lives, 25% of the original amount would be present.)*

Only those isotopes with half-lives longer than 100 days are considered as potential fuel for direct conversion systems. To achieve the necessary temperature in a suitably

Radioisotope auxiliary power generators being built today usually employ thermoelectric conversion systems since their performance is reasonably well advanced. Acceptable efficiencies of 5 to 6% may be obtained at temperatures up to about 1000 F, at which point today's thermoelectric materials themselves become limiting. High-temperature materials probably can be developed in the future to yield efficiencies as high as 15%. These efficiencies may be compared with the 30 to 35% efficiency of conventional steam plants generating electricity.

The SNAP-1A unit mentioned earlier was developed to provide electricity for space applications such as the Discoverer-type satellite. SNAP-1A employs the radioisotope cerium-144, a fission product whose initial thermal output of 6500 watts will decay to the 2500 watts necessary to deliver 125 watts of electricity after one year in space.

The time-predictable excess heat of radioisotope decay is radiated to space by a shutter control system during the first year to maintain constant power output. SNAP-1A has a flyaway weight (the liquid mercury shield is drained prior to launching) of less than 200 lbs, is designed to endure the rigors of rocket-booster launching without system failure, and will deliver more than a million watt-hours of electrical power in one year. Approximately 37 tons of nickel-cadmium batteries would be required to deliver an equivalent amount of power.

While silicon solar cells are in wide use today for space applications, they are vulnerable to radiation and micrometeorite damage, and require precise orientation in space to achieve rated efficiencies. High-efficiency solar cells (10%) are costly, their efficiency decreases with increasing temperature, and substantial losses occur in their electrical collection networks. For many missions — including those where the power unit is exposed to a short period of sunlight — solar cells are not considered desirable.

More heat, more power

A second device for direct conversion — the thermionic converter or generator—is similar to a vacuum diode in that it consists of an anode and a cathode enclosed in an evacuated space. *(See "Thermionics," page 50.)*

Thermionic generators become more efficient as their operating temperatures increase. The practical operating temperature range of thermionic isotopic power systems begins where today's thermoelectric generator temperature range ends. Thermionic converters are capable of achieving 15 to 20% efficiencies at relatively high heat source and radiator temperatures.

Actively associated with the atomic energy industry for 17 years, Dr. Charles E. Crompton was a member of the plutonium research team at the University of California in 1943. A physical chemist by background, he completed his doctoral work after wartime service with the Manhattan Project. He was deputy director of the AEC Isotopes Div. for several years.

Space uses demand high temperatures to achieve efficient heat rejection by radiation. Therefore, thermoelectric converters appear to be inherently inferior to thermionic converters with respect to both maximum efficiency and power-to-weight ratio (watts per pound).

Since 1958, the AEC Missiles Project Branch has sponsored work on isotopically fueled thermionic generators. Thermo Electron Engineering Co., Waltham, Mass., has been the subcontractor for the thermionic portion of the device. This work has included dynamic testing of electrically heated (simulated isotope heat) generators and presently is directed toward a curium-242 unit producing eight to 10 watts of power for space use. Curium-242, with its high power density (120 watts per gram), is required to achieve the high emitter temperature necessary.

Close-spaced diodes—the spacing is 0.0004 in. — are employed to minimize inefficiency arising from the electrical space-charge phenomenon encountered between the cathode and anode. Close-spaced diodes operate with an emitter temperature of 2200 F and above, and efficiencies of 5 to 7% are presently available. Power densities of one to two watts per square centimeter of emitter area are possible. They reflect the compactness and high power-to-weight ratio inherent in this type of converter.

The first prototype close-spaced thermionic generator employed a simulated radioisotope heat source to permit thorough performance testing. It is a single-stage vacuum diode with an oversized spacing of 0.001 in. which, at its 1400 K operating temperature, limits its output to slightly more than a half watt per pound at 1% efficiency.

This prototype, still operating satisfactorily after 2100 hours at 1400 K, is the forerunner of radioisotope-heated devices which will produce 15 to 20 watts per pound at efficiencies of about 10%.

Radioisotope-fueled thermionic generators hold tremendous promise for future space applications. To realize this potential, it is necessary to utilize substantial quantities of high power-density alpha-emitting radioisotopes such as curium-242 and plutonium-238. Unfortunately, however, these rare isotopes have not been produced in greater than research quantities by the AEC; hence neither a supply nor a processing facility exists to meet this need.

Reflecting industry's confidence in the use of such radioisotopes as heat sources for auxiliary power systems, Martin recently constructed a heavy elements processing facility at Baltimore for processing americium-241 into suitable irradiation targets required for the production of curium-242 in a nuclear reactor. The Martin hot cell facility to accomplish separation of curium from the irradiated targets is located at Quehanna, Pa.

The logistics of many present auxiliary power applications lead to high costs due to refueling with conventional fuel or to maintenance and equipment replacement. Under such circumstances, isotopic power systems offer a singular advantage.

An exhaustive safety and hazards evaluation study accompanied development of radioisotope-fueled power sources. For example, basic to strontium-90 systems was the development of an unusually inert chemical compound of strontium having a high melting point, an acceptable high power density, and good thermal conductivity, while at the same time being extremely insoluble in fresh and sea water. After testing many materials, the unusually attractive properties of strontium titanate were found to meet these stringent criteria.

Radioactive strontium-90 was employed in tracer amounts to study and determine the precise solubility of strontium titanate in sea water. Because of the combined effect of natural radioactive decay of strontium-90 and the extremely slow rate of solution of this titanate com-

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pound (1.5 micrograms per day per square centimeter of pellet surface), a maximum of 0.5% of the total strontium-90 would exist in soluble form in sea water, and this would be achieved 40 years after immersion.

Five-century resistance

To prevent even this condition from being realized, a containment or encapsulating material that would withstand corrosive attack by sea water was sought. Hastelloy C, an alloy produced by Haynes Stellite Co., Div. of Union Carbide Corp. has been tested for more than 10 years at Wrightsville Beach Testing Station, N.C., and is known to be consumed at the rate of 0.0001 in. per year. Therefore, a capsule of Hastelloy C with walls one-quarter inch thick was employed to contain the strontium-90 fuel pellets. A capsule of this thickness is considered to withstand sea water corrosion for at least five centuries.

Under a general safety evaluation program for all types of isotope fueled generators, exhaustive tests were carried out to demonstrate physical strengths of various cladding and capsule materials and the completely assembled thermoelectric generator.

The test capsule was heated to its typical operating temperature (approximately 1000 F) and then was accelerated to 500 ft per second by a rocket sled, whereupon it was impacted against a granite slab. Assembled generators were similarly impact-tested at 500 ft per second. Having withstood this test without failure, the radioisotope capsule next was subjected to fire and explosion hazards in tests designed to simulate space missile accidents.

Baptism of fire

To simulate explosion of the booster propellant in a missile launch-stand failure, 1650 lbs of TNT was detonated. While the generator assembly did not survive these tests, of course, the radioactive fuel capsule did survive without rupture or leakage of its contents.

In view of the great potential advantage and versatility of radioisotope-powered auxiliary power systems, it is not surprising to find such an impressive amount of research, engineering design, and analysis devoted to the safety, performance, and reliability of these devices. Small, efficient, silent power sources are available for remote, unattended operation at costs competitive with existing power supplies having less desirable attributes. Improvements in the technology of this new field are expected to decrease power costs further. ■

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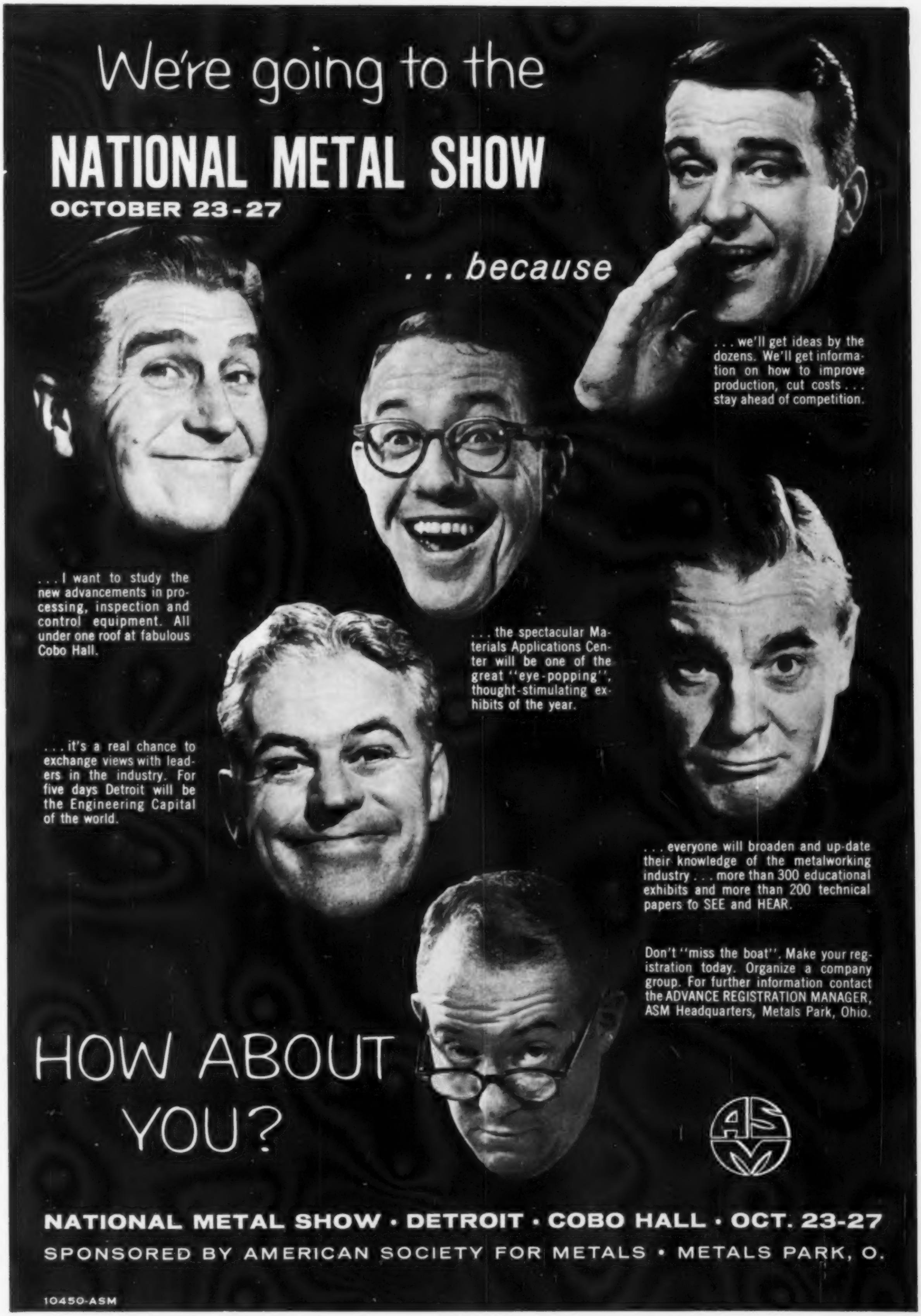
(For more employment opportunities, see page 84.)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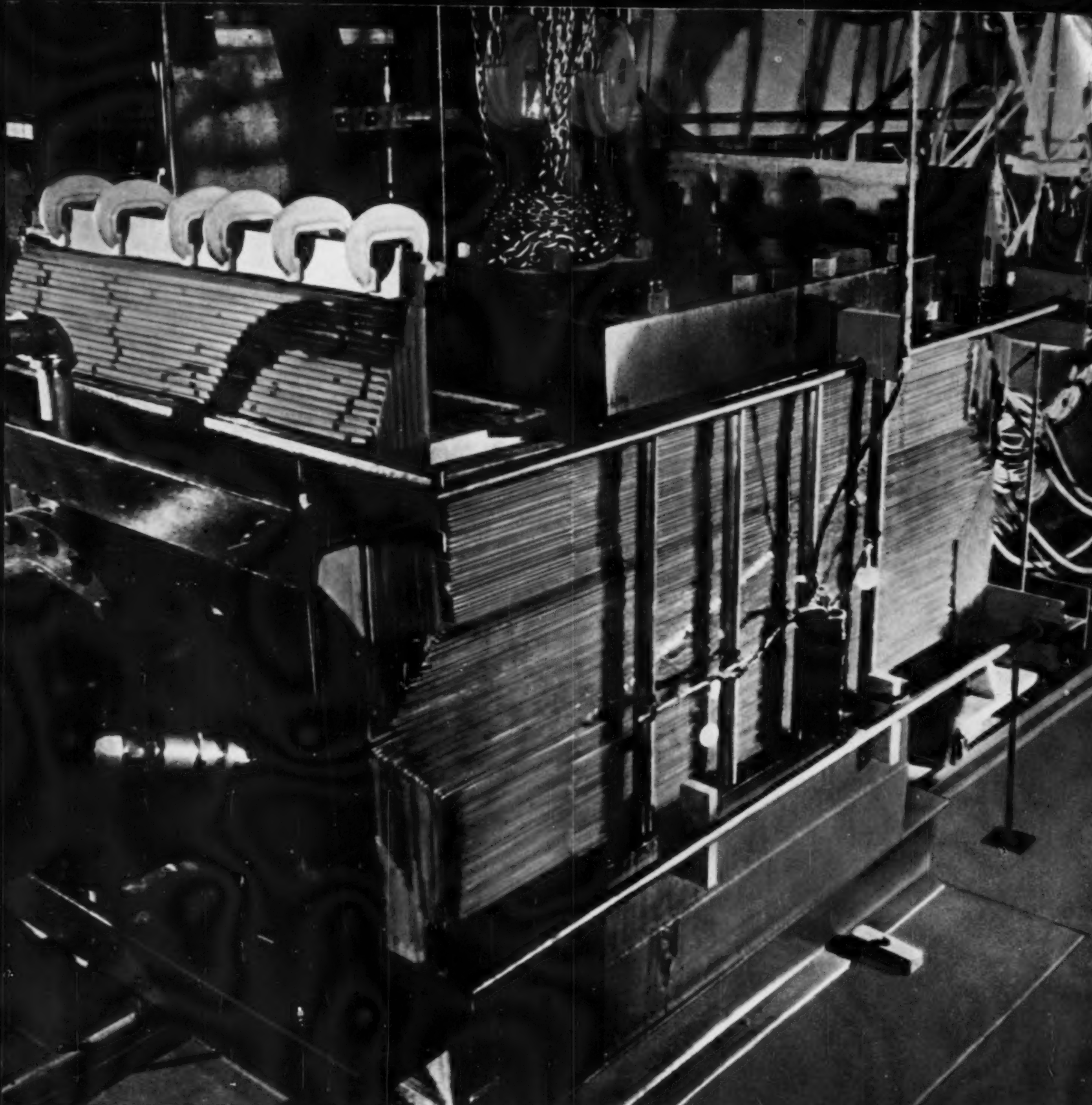

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